

CHARACTERIZATION AND ESTIMATION OF POWER GENERATION POTENTIALS OF SOME AGRICULTURAL WASTES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

Master of Technology(Research)

in

Mechanical Engineering

by

SATYABRATA TRIPATHY

Roll No: 612ME103



Dept. of Mechanical Engineering
National Institute of Technology, Rourkela
2015

CHARACTERIZATION AND ESTIMATION OF POWER GENERATION POTENTIALS OF SOME AGRICULTURAL WASTES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

Master of Technology(Research)

in

Mechanical Engineering

by

SATYABRATA TRIPATHY

Roll No: 612ME103

Under the supervision of

Prof. S. K. Patel and Prof. M. Kumar



Dept. of Mechanical Engineering
National Institute of Technology, Rourkela
2015

Declaration

I hereby declare that the work which is being presented in this thesis entitled **“Characterization and Estimation of Power Generation Potentials of Some Agricultural Wastes”** in partial fulfilment of the requirements for the award of M. Tech. (Research) degree, submitted to the Department of Mechanical Engineering, National Institute of Technology, Rourkela, is an authentic record of my own work under the supervision of Prof. S. K. Patel and Prof. M. Kumar. I have not submitted the matter embodied in this thesis for the award of any other degree to any other university or institute.

Place:

Date:

SATYABRATA TRIPATHY



NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

Certificate

This is to certify that the thesis entitled “**Characterization and Estimation of Power Generation Potentials of Some Agricultural Wastes**” submitted by **Satyabrata Tripathy**, Roll no. 612ME103 has been carried out under my supervision in partial fulfilment of the requirements for the award of **Master of Technology (Research)** degree in Mechanical Engineering with specialization in **Thermal Engineering** at National Institute of Technology, Rourkela, and this work has not been submitted to any other University/Institute for the award of any degree.

Prof. S. K. Patel

Prof. M. Kumar

Principal Supervisor

Co-supervisor

Department of Mechanical Engineering

Department of Metallurgy and Materials
Engineering

National Institute of Technology, Rourkela

National Institute of Technology, Rourkela

Email: skpatel@nitrkl.ac.in

Email: mkumar@nitrkl.ac.in

ACKNOWLEDGEMENT

I express my deep sense of gratitude and indebtedness to my supervisors Prof. S.K. Patel and Prof. M. Kumar for providing precious guidance, constant encouragement and inspiring advice throughout the course of this work and for propelling me further in every aspect of my academic life. Their presence and optimism has provided an invaluable influence on my career and outlook for the future. I consider it my good fortune to have an opportunity to work with two such wonderful persons.

I am grateful to Prof. S. S. Mahapatra, Head of the Department of Mechanical Engineering for providing me the necessary facilities for smooth conduct of this work. I am also grateful to Mr. Bhanja Nayak, Fuel Laboratory, Metallurgical and Materials Engineering for his assistance in experimental work. I am also thankful to all the staff members of the department of Mechanical Engineering and department of Metallurgical and Materials Engineering and to all my well-wishers for their inspiration and assistance. I would also like to thank Dilip Kumar Bagal, M.Tech. (Research) student of Mechanical Engineering department for helping in software work.

Satyabrata Tripathy

Roll no. 612ME103

Mechanical Engineering

National Institute of Technology, Rourkela

Abstract

India is developing at an incredible rate. With development, there is an alarming increase in the demand for energy. But at the same time, we as a nation, have to economize on our energy costs to focus on human developmental needs. It is an undeniable fact that we have to strive for energy self-sufficiency to stay relevant in the modern times we live in. In such context, the idea of biomass energy becomes very important and relevant. With its inherent advantages of carbon neutrality and sustainability, biomass energy is the way forward for the nation and the world at large. Biomass energy has the potential and the promise of becoming the prime energy source. Though many forms of bioenergy are in focus of many research and development agencies/organizations, harnessing the biomass energy through combustion is the simplest method. In this project, we attempt to analyse and discuss the feasibility and sustainability of this method. We would have to dwell upon the challenges posed by this method and attempt to quell these in a scientific manner. Abundant land and water resources are the major enabler for adoption of biomass energy, as a principle. But in practice, technical variables such as calorific value, ash content, presence of sulphur, greenhouse gas emissions play a significant role in the actual adoption of biomass as a major source of energy. To study these, we have chosen wastes of six different agriculture based biomass species such as banana (*Musa acuminata*), coconut (*Cocos nucifera*), arecanut (*Areca catechu*), rice (*Oryza sativa*), wheat (*Triticum aestivum*) and palm (*Borassus flabellifer*). The samples were analysed by proximate and ultimate analyses, and further correlation was established through regression analysis. Proximate analysis showed that the coconut has the highest volatile matter content (i.e., 73 wt.%) and banana has the highest fixed carbon content (i.e., 20 wt.%) which indicated higher calorific values. The determination of calorific values validated the former results. Palm exhibited lowest ash content suggesting no ash related problems during combustion. Ultimate analysis performed on some of the selected

species showed high carbon and hydrogen contents in the leaves of coconut and arecanut. Out of some selected biomass ashes tested for their fusion temperatures, rice has the lowest initial deformation temperature (i.e., 938 °C) which is substantially above the boiling temperature, suggesting that all the selected biomass samples can be used safely for combustion in boilers up to a temperature of 800 °C. The bulk density of rice husk has been found out to be the highest (i.e., 336.257 kg/m³), suggesting facilitation of higher amount of rice husk in the boiler and, economical transportation and handling. An attempt has been made to develop empirical formulae statistically using regression analysis to predict gross calorific value using proximate and ultimate analyses data. The land requirements for energy plantation with selected biomass species were computed and found that approximately 4931, 524, 1757, 814, 3043 and 1146 hectares of land for harvesting banana, coconut, arecanut, palm, wheat and rice biomass species for assuring a perpetual supply of electricity at the rate of 5475 MWh per year for a group of 10-12 villages consisting of about 2000 households. Further, from the calculations of fuel requirement it was observed that coal requirement can decrease from 4968.0 to 4289.1 t/year and 4968 to 4008.6 t/year with the increase in biomass content from 0 to 15 % in the briquettes of coal with rice husk and coal with palm leaf respectively which suggests that agricultural biomass wastes can be used in co-firing mode for generation of electricity by substituting a portion of coal.

Key words: Ash fusion temperature, Biomass, Bulk density, Calorific value, Proximate analysis, Regression analysis, Ultimate analysis

NOMENCLATURE

ΔT	Maximum rise in temperature
$\sum(Y - \hat{Y})^2$	Variation of Y value around regression line
$\sum(Y - \bar{Y})^2$	Variation of Y value around own mean
a_0, a_1	Constant parameters
AAE	Average absolute error
ABE	Average bias error
AC	Ash content
AFTs	Ash fusion temperatures
CHP	Combined heat and power plant
CSP	Concentrated solar thermal power plant
FC	Fixed carbon content
FT	Flow temperature
GCV	Gross calorific value
GDP	Gross domestic product
HHV	Higher heating value
HT	Hemispherical temperature
IDT	Initial deformation temperature
K	Number of independent variables
MC	Moisture content
MRA	Multiple regression analysis
MSW	Municipal solid waste
N	Number of data points in the sample
R	Coefficient of correlation
R^2	Coefficient of determination
RET	Renewable energy technologies
S	Standard error of estimate
SLRA	Simple linear regression analysis
SRA	Simple regression analysis
ST	Softening temperature
VM	Volatile matter content
W	Initial weight of dried sample
W.E.	Water equivalent of apparatus
wt. %	Weight percentage
X	Independent variable
Y	Sample values of dependent variables
\bar{Y}	Corresponding estimated values from regression analysis

LIST OF TABLES

Sl. No.	Detail	Page
Table 1.1:	Estimated Power Generation Potential from Renewable Energy in World [8-10].....	6
Table 3.1:	Local and Botanical Names of Selected Biomass Species	30
Table 5.1:	Proximate Analysis of Different Components of Studied Biomass Species	52
Table 5.2:	Ultimate Analysis of Different Components of Studied Biomass Species.....	54
Table 5.3:	Calorific Values of Different Components of Studied Biomass Species	56
Table 5.4:	Ash Fusion Temperatures of Different Biomass Samples.....	57
Table 5.5:	Proximate Analysis and Gross Calorific Values of Coal-Biomass (Rice husk) Mixed Briquette in Different Ratios.....	59
Table 5.6:	Proximate Analysis and Gross Calorific Values of Coal-Biomass (Palm leaf) Mixed Briquette in Different Ratios.....	59
Table 5.7:	Bulk Density of Selected Biomass Species	61
Table 5.8:	Uncertainty of Measurement of Proximate Analysis of Different Components of Studied Biomass Species	64
Table 5.9:	Uncertainty of Measurement of Gross Calorific Value of Different Components of Studied Biomass Species	65
Table 5.10:	Uncertainty of Measurement of Bulk Density of the Selected Biomass Species	66
Table 5.11:	Uncertainty of measurement of proximate analysis and gross calorific value of Coal- Biomass (Rice husk) Mixed Briquette in Different Ratios	67
Table 5.12:	Uncertainty of measurement of proximate analysis and gross calorific value of Coal- Biomass (Palm leaf) Mixed Briquette in Different Ratios.....	67

Table 5.13: Developed Regression Equations for the Estimation of the Gross Calorific Values of Studied Biomass Samples from Proximate Analysis Data and Their Statistical Performance Measures	70
Table 5.14: Developed Regression Equations for the Estimation of the Gross Calorific Values of Studied Biomass Samples from Ultimate Analysis Data and Their Statistical Performance Measures	73
Table 5.15: Total Energy Contents and Power Generation Structure for Banana	75
Table 5.16: Total Energy Contents and Power Generation Structure from Coconut Biomass Species.....	76
Table 5.17: Total Energy Contents and Power Generation Structure from Arecanut Biomass Species.....	76
Table 5.18: Total Energy Contents and Power Generation Structure from Rice Biomass Species	77
Table 5.19: Total Energy Contents and Power Generation Structure from Wheat Biomass Species.....	77
Table 5.20: Total Energy Contents and Power Generation Structure from Palm Biomass Species	77
Table 5.21: Land Required for Energy Plantation of Different Agricultural Biomass Species for generating 15 MWh per day	79
Table 5.22: Energy Content from Coal-Rice Husk Blends.....	80
Table 5.23: Energy Content from Coal-Palm Leaf Blends.....	80
Tables 5.24: Fuel Required for Coal-Rice Husk Briquettes	83
Tables 5.25: Fuel Required for Coal-Palm Leaf Briquettes	83

LIST OF FIGURES

Sl. No.	Detail	Page
	Fig 1.1: Estimated Power Generation Potential from Renewable Energy in India	7
	Fig 1.2: Installed Power Generation Potential from Renewable Energy in India	8
	Fig 3.1: Bomb Calorimeter	35
	Fig 3.2: Leitz Heating Microscope.....	37
	Fig 3.3: Different Ash Fusion Temperatures	39

CONTENTS

Sl. No.	Detail	Page
	Declaration	i
	Certificate	ii
	Acknowledgement	iii
	Abstract	iv
	Nomenclature	vi
	List of Tables	vii
	List of Figures	ix
	Chapter 1 INTRODUCTION.....	1
1.1	Overview	2
1.2	Biomass	4
1.2.1	Applications of biomass energy	4
1.3	Why Biomass Energy?	5
1.4	Electric Power Generation Potential of Renewables.....	5
1.5	Biomass Conversion Process.....	8
1.5.1	Combustion	8
1.5.2	Thermochemical process.....	9
1.5.3	Biochemical conversion	10
1.6	Biomass: Potential Substitute of Coal for Power Generation	10

1.6.1 Biomass co-firing technology	11
1.7 Benefits of Utilizing Biomass for Power Generation.....	12
Chapter 2 LITERATURE REVIEW	14
2.1 Introduction	15
2.2 An Outline of Energy Challenges in India	15
2.3 Renewable Energy Scenario.....	16
2.4 Biomass and its Potential	18
2.5 Biomass Conversion Process.....	20
2.6 Fuel Characteristic of Biomass.....	22
2.7 Ash Fusion Temperature	23
2.8 Co-firing of Biomass with Coal	24
2.9 Regression Analysis on the basis of Proximate and Ultimate Analysis	25
2.10 Decentralized Power Generation	26
2.11 Summary	26
2.12 Objectives	27
Chapter 3 EXPERIMENTAL WORK	28
3.1 Introduction	29
3.2 Selection of Materials.....	29
3.3 Proximate Analysis.....	30
3.3.1 Determination of moisture content.....	31
3.3.2 Determination of ash content	31

3.3.3	Determination of volatile matter	32
3.3.4	Determination of fixed carbon content.....	33
3.4	Calorific Value Determination	33
3.5	Determination of Ash Fusion Temperatures	36
3.6	Ultimate Analysis	40
3.7	Bulk Density of the Selected Agricultural Residues	40
3.8	Uncertainty of Measurement	40
3.8.1	Standard Deviation	41
3.8.2	Propagation of Uncertainty	41
Chapter 4	REGRESSION ANALYSIS	43
4.1	Introduction	44
4.2	Regression Analysis	44
4.3	Linear Regression Analysis.....	45
4.3.1	Simple linear regression analysis	45
4.3.2	Multiple linear regression analysis.....	46
4.4	Parameters of Regression Analysis	46
4.4.1	Standard error of estimate	46
4.4.2	Coefficient of determination	47
4.4.3	Coefficient of correlation	48
4.5	Evaluation of Errors	48

Chapter 5 RESULTS AND DISCUSSION	49
5.1 Introduction	50
5.2 Chemical Compositions of the Studied Biomass Species	50
5.2.1 Proximate analysis.....	50
5.2.2 Ultimate analysis	53
5.3 Calorific Value	55
5.4 Ash Fusion Temperatures.....	56
5.5 Analysis of Co-firing Potentials of Mixed Briquettes of Coal-Selected Biomass Species ...	58
5.6 Bulk Density.....	60
5.7 Determination of Uncertainty.....	61
5.8 Regression Analysis	68
5.8.1 Regression analysis performed on proximate analysis data.....	68
5.8.2 Regression analysis performed on ultimate analysis data	71
5.9 An Approach for Decentralized Power Generation and Energy Plantation Structure	74
5.9.1 Land requirement for biomass.....	75
5.9.2 Fuel Requirement for co-firing with biomass	79
a) <i>Amount of fuel required when proportion of coal-rice husk is 100:0 (i.e., 100 %</i> <i>coal)</i>	81
b) <i>Amount of fuel required when proportion of coal-rice husk is 90:10 (i.e., 90 % coal</i> <i>and 10 % rice husk)</i>	81

<i>c) Amount of fuel required when proportion of coal-rice husk is 85:15 (i.e., 85 % coal and 15 % rice husk)</i>	<i>82</i>
Chapter 6 CONCLUSIONS	85
6.1 Conclusions	86
6.2 Scope for Future Work	87
REFERENCES	88

Chapter 1

INTRODUCTION

- *Overview*
- *Biomass Energy*
- *Why Biomass Energy?*
- *Electric Power Generation Potential of Renewables Globally*
- *Scenario of Power Generation Potential of Renewable Sources in India*
- *Biomass Conversion Process*
- *Biomass: Potential Substitute of Coal for Power Generation*
- *Benefits of Utilizing Biomass for Power Generation*

1. INTRODUCTION

1.1 Overview

Fossil fuels are the primary source of generation of electricity globally. Conventional thermal power plants and other industries consume enormous quantity of fossil fuel reserves which are non-renewable and are available in limited quantity. The fast depletion of fossil fuels, economic issues and environmental concerns over emission from conventional power plants has compelled researchers to strategize the fuel mix. Therefore, the quest for the alternative sources of electricity generation which should be eco-friendly and renewable is crucial in order to decrease our reliance on conventional sources of energy.

In India, about 63 million hectares is covered by forest with a deforestation rate of around 3 lakh ha/year [1]. In addition to the barren land (around 30 million hectares) available for forestation and forest residues, about 500 MT of agricultural residues are generated every year from agricultural lands [2]. Agriculture is the mainstay of rural India, constituting 70 % of total population and 198.9 million hectares of gross cropped area with a cropping intensity of 140.5 %. It also contributes significantly in India's economic sector with a share of approximately 13.9 % of India's gross domestic product [3]. Due to wide spread practices of agriculture, lots of agricultural wastes are generated which remains unutilized.

India stands ninth as the largest economy in world, with GDP growth of 8.7 % and 7.5 % in the last 5 and 10 years respectively. This eminent rise in economic development is laying tremendous demand on energy resources which may cause India to confront energy supply constraints. Around 70 % of electricity generated in India is produced from coal fired plants and during 2011-12, India was the fourth largest in consumption of natural gas and crude oil [4]. The

limited coal resource and other traditional sources make it imperative to explore for an optimal energy mix in order to manage the imbalance in demand and supply of energy. Exploring and exploiting alternative source of energy can be the answer to all the questions raised regarding energy security.

Biomass has become indispensable and enthralling way of power generation in India due its accessibility, lower investments and high energy potentials. Sustainable production and proper utilization of biomass can solve the problems in context to energy crisis, climatic concerns, power transmission losses, waste land development and rural unemployment [5]. Alongside supplying electricity to national power grids, biomass can be exploited for the opportunities it offers for decentralized power generation in rural areas. Considering all accounts, exploring and exploiting biomass can be the most prosperous source of renewable energy for developing countries including India.

All the projects on biomass have exhibited success hugely, yet the research and total exploitation of biomass is incipient. The design and efficiency of power plants largely depends on the properties of bio-fuels which vary from species to species. In order to recognize true potential of bioenergy in generation of electricity, it is essential to have complete knowledge of their fundamental properties like energy values, chemical composition including proximate and ultimate analyses, bulk density, ash fusion temperatures, etc. [6]. Studies and the findings of proximate analysis, ultimate analysis, calorific values, bulk densities, ash fusion temperatures and regression analysis to calculate heating values from proximate and ultimate analyses data of different components of six biomass species namely banana, coconut, arecanut, rice, wheat, and palm, and their impact on power generation has been outlined and discussed in this project.

1.2 Biomass

It is the biodegradable organic material derived from plants, microorganisms, and animals which includes by-products and residues from agricultural industries, forestry and biodegradable organic waste from industrial and municipal operation. Biomass is the most promising renewable energy because of its diverse quality of being used in any state of matter which makes it as the second largest renewable energy source on earth. World's total energy consumption is around 12 % which is expected to increase in future [7].

Biomass has become the most valuable renewable energy source of the century due to its ease of utilization in generation power. Excluding thermochemical and biochemical conversion processes which are frequently used, the direct combustion of biomass and co-firing it with coal has increased lot of opportunities and potential of biomass as a source of power generation because of immense availability, potential to be reused, and absence of pollutants.

1.2.1 Applications of biomass energy

Given the diverse quality of biomass, biomass energy can be applied to various applications such as:

- a) It can be used as solid fuel for combustion to produce heat or it can be also used in combined heat and power (CHP) plants.
- b) It can be blended with fossil fuels (co-firing) to improve efficiency and reduce the residues of combustion in the boiler.
- c) It can potentially replace petroleum as a source of fuel for transportation.
- d) In conjunction with fossil fuels biomass can be utilized to generate electricity.

1.3 Why Biomass Energy?

Biomass energy is an attractive energy source due to various reasons such as:

- a) It is a renewable energy source derived by natural processes as well as a byproduct of human activity and a surety of long term supplies.
- b) It is distributed more evenly all over the world than fossil fuels and can be harnessed by using more cost effective ways.
- c) It provides an opportunity to be more energy self-sufficient and helps in reducing climate change.
- d) Decentralized power generation from biomass offers rural job opportunities. It helps farmers, ranchers and foresters in managing the waste material in a proper way in order to harness energy.

1.4 Electric Power Generation Potential of Renewables

According to the Global Status Reports, an estimated 19 % of total energy consumption was provided by renewable energy sources, with a projection of nearly 25 % by 2040. This demand of energy was accomplished by modern renewables by an estimation of 4.2 %, hydropower by 3.8 % and 2 % of total energy consumption was provided by wind, solar, geothermal and biomass in 2014 [8-10].

In 2014, global electric power capacity from renewable energy sources reached a staggering 1560 GW, growth of 8 % over 2012. Apparently from Table 1.1, power generation from biomass went past 88 GW, growth of 18 % over 2012 and other renewables collectively produced more than 560 GW which is a growth of 7 % over previous year. Renewable sources contributed more than 56 % of net additions to electricity generation capacity globally in 2013 [10].

Table 1.1: Estimated Power Generation Potential from Renewable Energy in World [8-10]

Technology	Electric Power Capacity in GW		
	2012	2013	2014
Bio-Power	72.0	83.0	88.0
Geothermal Power	11.2	11.7	12.0
Hydropower	970.0	990.0	1000.0
Ocean Power	0.5	0.5	0.5
Solar Power	70.0	100.0	139.0
Concentrated Solar Thermal Power Plant (CSP)	1.8	2.5	3.4
Wind Power	238.0	283.0	318.0
Total	1363.5	1470.7	1560.9

The power generation potential from renewable energy source is estimated to be around 94125 MW as per the report of Ministry of Statistics and Programme Implementation in 2014, which included power generation from wind (49130 MW), small hydropower (19750 MW), biomass (17538 MW) and cogeneration bagasse (5000 MW) as shown in Fig. 1.1. The geographic distribution of estimated power generation capacity from renewables demonstrates that Karnataka has the highest contribution of about 15.37 % (14464 MW), closely followed by Gujrat with 13.27 % (12494 MW) and Maharashtra with 10.26 % (9657 MW) [4].

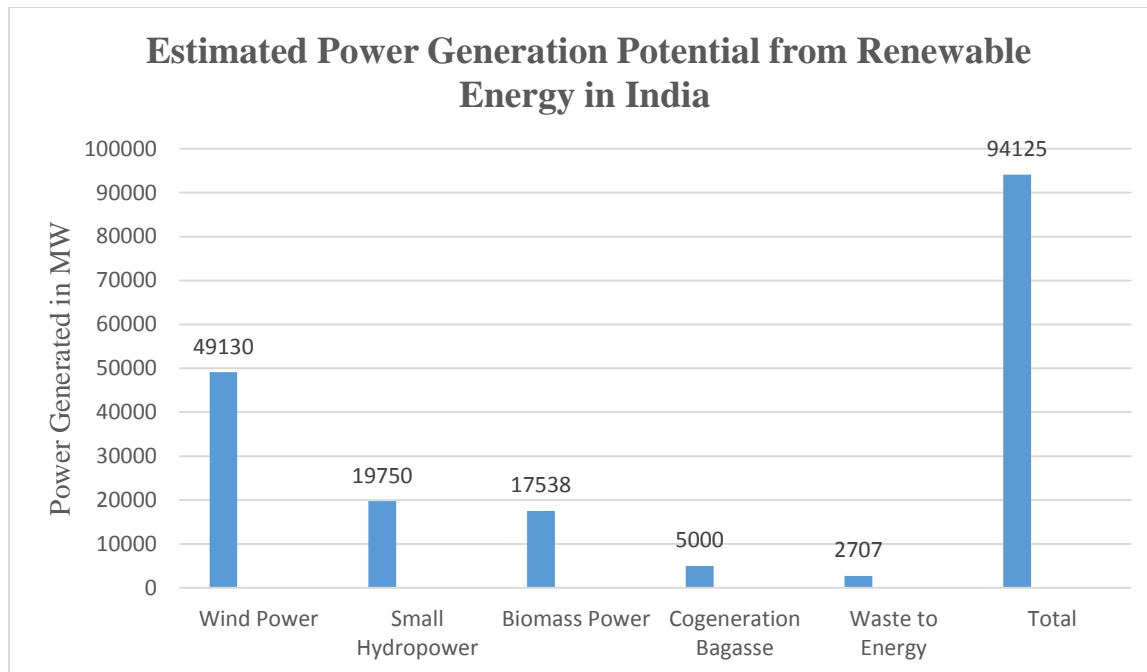


Fig 1.1: Estimated Power Generation Potential from Renewable Energy in India [4]

As per the global stipulation on the carbon emission and sustainability through various changes, Indian energy sector is flourishing and dedicated towards increasing the contribution of renewable power in total energy production. It has been projected that 15 % of total power generation will be supplied by renewable energy source by 2020. New initiatives are being launched by Government of India to restrict the issues related to climate emerging during power generation. Ministry of New and Renewable Energy together with Ministry of Power has launched an eco-friendly energy solution initiative called Jawarharlal Nehru National Solar Mission, with an objective to set up 20000 MW grid of solar power by 2022. In 2012, over 2800 MW capacity of wind energy was installed taking the renewable power capacity up to 22000 MW. In 2011, power generated from solar crossed 100 MW milestone and over 1000 villages of remote areas were electrified [11]. The installed capacity of power generation from renewable energy sources are listed in Fig. 1.2.

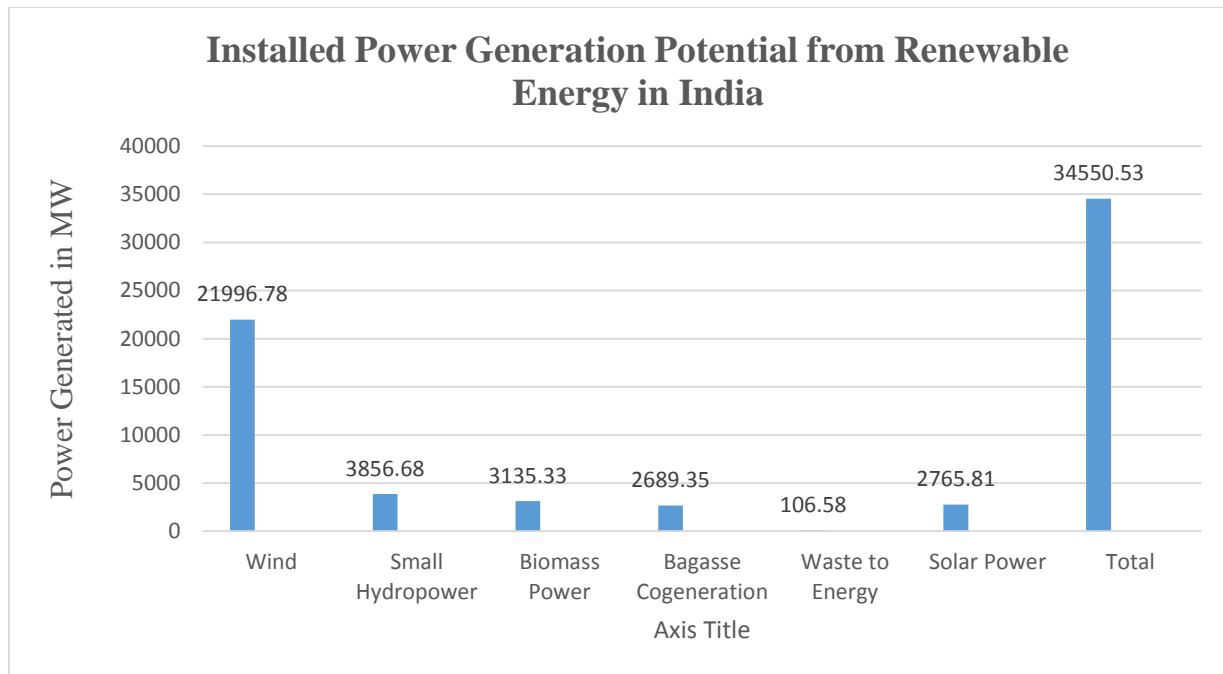


Fig 1.2: Installed Power Generation Potential from Renewable Energy in India [4]

1.5 Biomass Conversion Process

The progress of biomass conversion technologies has shown tremendous development in the recent past. Various conversion technologies for generation of electricity from biomass are as follows.

1.5.1 Combustion

a) Direct Combustion

This is the most common combustion method of feedstock residues like woodchips, sawdust, bark, bagasse, straw, MSW, etc. This method is employed to produce heat or steam in the boiler usually in the two stages, first stage is for drying and partial gasification and finally complete combustion in second stage. This method is not desirable because of generation of high amount of moisture during combustion [12].

b) Co-firing

Co-firing is a fuel-switching strategy in which two different fuels are used for combustion in the boiler. In conventional power plants, biomass can be blended with coal in the boiler with some minor changes. The results from the experiment manifested that around 5-20 % of biomass can be blended with coal for combustion in boilers. Utilization of biomass along with coal for power generation has shown huge reduction in emission of carbon dioxide, SO_x and NO_x [13].

1.5.2 Thermochemical process

a) Pyrolysis

Pyrolysis is a thermochemical decomposition of organic matter in the absence of oxygen at high temperature (430 °C). Generally, pyrolysis of organic substances leaves behind a solid residue which is rich in carbon content and extreme pyrolysis leaves mostly carbon as residue and is called carbonization [14].

b) Torrefaction

It is a thermochemical treatment of biomass at 200-300 °C under atmospheric pressure and in absence of air. During the process, biomass loses around 20 % of its mass and after it is torrefied, it can be densified to increase its mass and energy density. Torrefaction together with densification can be exploited to overcome logistic issues in case of eco-friendly production of electricity [14].

c) Gasification

It is conversion of biomass into gas under high temperature and in a controlled environment. This process is usually carried out in two stages in which producer gas and charcoal is produced

in the first stage by partial combustion of biomass at about 800 °C. In the subsequent stage, CO₂ and H₂O formed in the first stage are reduced chemically to get CO and H₂ with 18-20 % H₂, an equal portion of CO, 2-3 % CH₄, 8-10 % CO₂ and rest nitrogen [15].

1.5.3 Biochemical conversion

a) Anaerobic Digestion

It is the breakdown of biodegradable materials like animal manures, energy crops, organic wastes, etc. by microorganisms into biogas which is 40-75 % methane gas rich and contains small traces of hydrogen sulphide and ammonia. This biogas can be utilized for heating or cooking purposes, generation of electricity or motive power, etc. [16].

b) Alcoholic Fermentation

Alcoholic fermentation is also referred as ethanol fermentation. It is a bio-chemical process in which biomass is converted into sugar or other feedstock and fermented using microorganisms to produce fuel grade ethanol. Ethanol produced from indigenous biomass can stimulate new markets for agricultural sector and increasing domestic employment [17].

1.6 Biomass: Potential Substitute of Coal for Power Generation

More than 70 % of electricity is generated by coal based power plants which emits carbon dioxide and other greenhouse gases which is hazardous to human race. In addition to the pollution caused by coal fired plants, it requires huge capital investment with a lifespan of only 20 to 50 years. It is not feasible to completely retire these conventional plants but can effectively be used by substituting some portion of coal with biomass to generate clean energy. This effective replacement of conventional fuel with biomass for power generation is known as co-

firing. Further, co-firing coal with biomass is a valuable tool decrease emission of greenhouse gases and other pollutants in coal-fuelled plants.

1.6.1 Biomass co-firing technology

Co-firing coal with biomass has the potential to reduce emissions from coal based power generation without substantial increase in costs or infrastructure in a short duration. Partial substitution of biomass for coal has shown tremendous potential as an option for emission reduction and efficient generation of power. Various types of co-firing are as follows:

a) Direct Co-firing

Direct co-firing is defined as the combustion of two heterogeneous fuels in a boiler. Usually, biomass is milled and added directly with the pulverized coal for a better combustion. Use of up to 20 % of biomass fuel is proved to be effective in this process. But, due to variation in energy values and ash contents, some ash related problems along with corrosion could take place.

b) Indirect Co-firing

It is a less generalized process which is complex and extreme. In this process, a gasifier is employed to convert the solid bio-fuel to flue gas. It is an efficient process as there is reduction in corrosion and fouling of boilers. Also, a large portion of coal can be replaced with the generated flue gas. In addition to above, fuels containing heavy metals can be used in this process.

c) Parallel Co-firing

In parallel co-firing, separate combustion processes are incorporated for both biomass and coal. The steam generated during biomass burning is fed directly to the coal-fired plant which

increases the boiler pressure and temperature. This technique is regularly used in paper industries for better utilization of the by-products obtained from paper production [18].

1.7 Benefits of Utilizing Biomass for Power Generation

There are various advantages of using biomass for power generation as listed below.

- a) Biomass can be utilized throughout the year whereas solar and wind are periodic in nature. Moreover, the uniform distribution of biomass worldwide compared to the presence of conventional fossil fuels in specific places on earth makes it more significant and valuable source of energy.
- b) Biomass takes carbon dioxide from the atmosphere and converts it into oxygen during photosynthesis reaction. Thus, the utilization of biomass for generation of power will certainly lower the carbon dioxide concentration in environment and consequently the greenhouse effect.
- c) As compared to coal, biomass has low ash content and its utilization will reduce the levels of suspended particulate matters in the atmosphere in considerable amount.
- d) Some of the biomass has higher calorific value than that of coals which are mostly used in Indian power plants.
- e) The high reactivity of biomass towards oxygen and carbon dioxide than that of coal allows the boiler to operate at lower temperatures ensuring significant energy saving.
- f) The installation of biomass gasifiers is viable in any locality particularly near villages and decentralized power generation cuts down the transmission losses.

- g) Decentralized power generation from biomass helps local farmers to manage waste material in a proper way so that it can be exploited to its true potential. It also provides opportunities for rural employment and new socio-economic possibilities.
- h) Plantation of biomass will prevent soil erosion and proper exploitation of biomass in generation of power will direct the attention of scientists and researchers towards better usage of barren lands.

Chapter 2

LITERATURE REVIEW

- *Introduction*
- *An Outline of Energy Challenges in India*
- *Renewable Energy Scenario*
- *Biomass and its Potential*
- *Biomass Conversion Process*
- *Fuel Characteristic of Biomass*
- *Ash Fusion Temperature*
- *Co-firing of Biomass with Coal*
- *Regression Analysis on the basis of Proximate and Ultimate Analysis*
- *Decentralized Power Generation*
- *Summary*
- *Objectives*

2. LITERATURE REVIEW

2.1 Introduction

In this chapter, the literature survey related to characterization and estimation of power generation potential of biomass species has been discussed. This chapter enlightens about the energy challenges and present energy scenarios prevailing in India as well as other nations. A review of biomass as alternate source of energy, its conversion processes and the ash fusion temperatures has been outlined briefly. This chapter also reviews various statistical methods adopted to predict gross calorific value and decentralized power generation structure from biomass.

2.2 An Outline of Energy Challenges in India

An enormous demand in energy has been agitated by this sustained economic growth, and the imbalance in demand, and supply requires effort to augment energy supplies as India confronts severe energy supply constraints. The 12th Plan document of the Planning Commission estimates that total domestic energy production will be around 669.6 million tonnes of oil equivalent (MTOE) by 2016-17 and 844 MTOE by 2021-2022, and the remnant to be coped with imports which are projected to be around 267.82 MTOE and 375.68 MTOE by 2016-2017 and 2021-22 correspondingly. During the 11th Five Year Plan, 70 % of the total electricity generation capacity was coal based. And other renewable sources such as wind, geothermal, solar, and hydroelectricity makes up a 2 percent share of the Indian fuel mix whereas nuclear holds an one percent share [19].

Analysis on India's energy consumption pattern of oil and oil products, and the composition of India's oil import sources reports the hovering risks as India imports 70 % of its

oil requisites. *Rastogi* [20] conjured up structural adjustments in the energy sector by developing and exploiting renewable sources of energy, developing energy infrastructure, enforcing consumption standards and technologies, diversifying the fuel mix and import sources of oil, creating tactical domestic reserves of oil and acknowledging a manageable extent of imports. A holistic energy security model is the need of hour to secure India's energy future.

India's need for energy and alternatives for low carbon with 20 year perspectives was analysed. The potential to reduce CO_2 emissions and the associated costs involved in various options were investigated as well. The survey showed that reduction in CO_2 emissions is executable up to 30 % by 2030 but it would call for additional costs. *Parikh and Parikh* [21] came to the conclusion that energy demands should be minimized by enforcing various methods to enhance energy use efficiency in production and consumption, and suitable options lie in nuclear, solar and energy efficiency and conservation.

2.3 Renewable Energy Scenario

India is focussed towards raising contribution of renewable power in the electricity mix to 15 % by the year 2020. The National Solar Mission targets to set up 20000 MW grid solar power and 2000 MW of off-grid capacity including 20 million solar lighting systems in around 20 million square meters solar thermal collector area by 2022. The wind energy sector was reinforced by adding over 2800 MW capacities resulting in grid-connected renewable power capacity crossing the 22000 MW milestones. During 2011, grid-connected solar power plants transpired over the 100 MW milestones. Over 1000 remote villages were electrified through renewable energy systems during this year. A total capacity of 15880 MW of wind power has been installed in the country [11].

Renewable energy technologies (RETs) are being installed to elevate renewable energy in India substantially considering high rate of growth of energy consumption, high percentage of coal usage, significant dependence on imports and unpredictability of world oil market. A recent survey by *Bhattacharya and Jana* [22] showed that, India is ranked fourth in world for harnessing wind energy, second in biomass program, solar water heaters are acquiring momentum and hydro energy is developing steadily. They called forth for reduction in greenhouse gas, encouragement of rural electrification program and supervision of oil import level, which should promote future prospects of renewable energy.

Global warming, increasing population and future energy security are the factors which forces the desire to approach modern energy and RETs as the means to deliver low carbon alternatives. A survey on rural energy in the state of Maharashtra highlighted the opportunities and attitudes of the inhabitants towards sustainable modern energy services, and the technologies used to deliver them. On the results of the work, *Blenkinsopp et al* [23] laid out a way to meliorate RET acceptance in rural communities.

The status and potential of different renewables in India was reviewed keeping a record of the trends in the emergence of it and a diffusion model as a basis for setting up goals was demonstrated. From the estimation of the economic viability and greenhouse gas saving potential for each option, it was found that several renewables have a high growth rates. New technologies like Tidal, solar thermal power plants and geothermal power plants are being manifested and future exposure will reckon on the experience of these projects. *Pillai and Banerjee* [24] suggested that the potential for renewable can be recognized by encouraging innovation and entrepreneurship in renewable.

The renewable energy scenario of India was reviewed and the future developments were deduced by considering the consumption, production and supply of power. An overview of the renewable energies in India while evaluating the current status, the energy needs of the country and forecasted consumption and production, with the objective to assess whether India can sustain its growth and its society with renewable resources was presented by *Gera et al* [25]. Hence they concluded that there is an urgent need to modulate the petroleum-based energy systems to renewable resources based systems, in order to decrease reliance on depleting reserves of fossil fuels and to extenuate climate change.

2.4 Biomass and its Potential

The outcomes regarding the combustion of agricultural residues giving attention to the glitches accompanied with the properties of the residues such as bulk density, ash melting points, volatile matter contents and the presence of nitrogen, sulphur, chlorine and moisture contents were discussed extensively. Agricultural residues which account 33 % of total residues has surplus significance as concerned to global warming as its combustion has the potential to be carbon dioxide emission neutral. Low bulk densities of agricultural residues suggested them to opt an effective transportation, storage and firing or usage of residues at the point of generation. Low melting point of ash possesses the threat of agglomeration, fouling, slagging and corrosion, but this can be eradicated by choosing proper combustion system. High content of volatile matter and low densities of particles resulted in emission of unburnt pollutants and flue gas. To solve this problem, an apt furnace design and application of staged combustion should be incorporated [26].

A bio-refinery concept which produces bioethanol, bioenergy and bio chemicals from two types of agricultural residues was studied. A system using a Life Cycle Assessment approach was investigated by taking into account all the input and output flows occurring along the production chain considering greenhouse gas emissions and primary energy demand taking climate change mitigation and energy security into account. Results showed reduction of greenhouse gas emissions, more non-renewable energy was saved and a higher eutrophication potential of bio refinery systems. A residues-based bio-refinery concept was suggested and it was able to solve the problems of finding a use for the abundant lingo-cellulosic residues and ensuring a mitigation effect for most of the environmental concerns related to the utilization of non-renewable energy resources [27].

About 17 GW of power can be generated from the available biomass through cogeneration, combustion and gasification routes. Assessment on the resource of non-plantation surplus biomass to use it for energy production and utilization in the Indian state of Haryana and Punjab by *Chauhan* [28] showed that out of total generated biomass, 45.51 % is intended as basic surplus, 37.48 % as productive surplus and 34.10 % as net surplus and power generation potential from these surplus biomass are 1.499 GW, 1.227 GW and 1.120 GW respectively. In the state of Punjab, survey revealed that 29 % of net surplus biomass was available for power generation. Further it was estimated that around 1.510 GW and 1.464 GW of power can be generated through basic surplus and net surplus biomass respectively [29].

The availability and potential of solid biofuels was discussed and the chemical mechanisms for the formation of pollutants during combustion were outlined. *Williams et al* [30] suggested that large combustion units can offer the best route to clean combustion because of the advantages of large scale efficient flue gas treatment plant but also they called for more detailed

analysis of basic features of biomass combustion and resultant pollutant formation and suggesting the analogy with the processes occurring in coal combustion is not adequate.

An experimental study by focusing on the suitability of using agricultural residues and power generation using direct combustion was carried out to compare the combustion of different agricultural residues in a single unit designed for wood pellets. A lower power input, higher oxygen levels and shorter cycles for ash removal was observed when agricultural residues were used, with all the biomass selected presented over 95 % relative conversion of fuel to CO₂. Experiment suggested that the size of the fuel particle and ash content have a great influence on the reactivity of char, and the relative conversion of fuel N to NO decreases at higher excess air ratios for most of the biomass fuels [31].

2.5 Biomass Conversion Process

The biomass based energy devices which are developed in recent times and emphasized the need for this renewable energy were analysed. *Mukunda et al* [32] classified biomass in terms of woody and powdery, and compared their energetics with fossil fuels. They discussed gasifier-combustor and gasifier-engine-alternator combinations, for generation of heat and electricity and emphasized the importance of biomass to obtain high-grade heat through pulverized biomass in cyclone combustors. The techno-economics was discussed to indicate the viability of these devices in the current world situation. The application packages were introduced where the devices will fit in and the circumstances, which was well-disposed for their seeding. The lack of acknowledgement of the genuine potential of biomass-based technologies was deduced as the important limitation for its use.

Three different biomass conversion processes viz., thermochemical, chemical and biochemical were reviewed on the basis of the results of some investigations and the important parameters for these three processes were identified. It was found that the efficiency of power generation and the range of uses can be increased by upgrading the biomass into gaseous or liquid fuel of higher energy density, which can be done by biological or thermochemical processes. *Kucuk and Demirbas* [33] identified that fermentation of sugar or esterification of vegetable oils may produce liquid fuel call bio-diesel and heating of solid biomass in the absence air can give char, gas or bio-oil through gasification or pyrolysis.

Biomass combustion ascribes about 60 % of the desired process energy in pulp, paper, and forest products and these processes can be enriched to the label of self-sufficiency of these sectors. Biomass industry manufactures ethanol by fermentation of sugar streams as well as lignocellulosic biomass which is not linked directly to food production. Biomass systems can be tailored for production of fuels viz., hydrogen, but the expenses of these technologies still needs to be deflated through research, development, demonstrations and diffusion of commercialized new technologies [34].

The technology of wood gasification which can induce a gas can be utilized in internal combustion engine was studied by developing a small fixed bed, stratified and open top gasifier in order to compute the performance of the gasification process. The mass and energy balances were obtained by considering several parameters and its cold gas, global and mass conversion efficiencies were determined. The recirculation of gas improved the efficiencies of the equipment and higher internal temperatures were achieved along with some operational problems like bridging and channelling, grate control and extensive wear of internal parts [35].

A pulverized fuel stove with enriched conversion efficiency and nominal emissions at near constant power level was developed. To affirm the stable combustion of the gases, a metal device was employed and duration of gasification was prolonged by the usage of a single port configuration. The problems of flame extinction in the single port configuration were figured out in a multi-port design with vertical air entry. The conversion efficiency was enhanced by 37 % and the CO emission performance was superior to conventional biomass stoves. They ended that the required power levels of operation can be accomplished by increasing port diameters [36].

2.6 Fuel Characteristic of Biomass

The modern biomass based transportation fuels such as fuels from Fischer–Tropsch synthesis, bioethanol, fatty acid methyl ester, bio-methanol, and bio-hydrogen was concisely reviewed and was assessed for various reasons like energy security reasons, environmental concerns, foreign exchange savings, and socioeconomic issues pertained to the rural sector. The results demonstrated that it is feasible that wood, straw and domestic wastes may be economically converted to bio-ethanol. Biofuels were derived from biomass by hydrolysis process and pyrolysis was the most significant process among the thermal conversion processes of biomass. Bio-diesel is an eco-friendly substitute liquid fuel which can be utilized in any diesel engine without any transfiguration [37].

Biomass is the only renewable fuel which is carbon based and biomass conversion systems can be assessed in the size range from a few kW to more than 100 MW. The heat yielded from biomass is highly efficient as well as economically viable. Thus, co-combustion of biomass with coal is encouraged as it coalesces high efficiency with sensible transport distances. The

emissions of pollutants like carbon mono-oxides, soot, polycyclic aromatic hydrocarbon, oxides of nitrogen and submicron particles can be governed effectively by employing various methods like air staging and fuel staging which has the potential of 50 % to 80 % reduction of these emissions. *Nussbaumer* [38] suggested establishment of secondary measures for required of biomass combustion and exploitation of alternatives to direct combustion of biomass.

2.7 Ash Fusion Temperature

The investigation on ash fusion characteristics of four different biomass species showed more unburned organic matter in Bermuda grass and bamboo due to sintering and higher calcium content in pine ash. They also studied ash fusion characteristics for co-combustion of biomass with coal. It was found that the ash melting temperature decreased at first and then increased, when the content of the corn straw was increased. They concluded that the ash melting temperatures are not affected by the ash temperature and biomass should be converted to ash at lower ash temperatures [39].

Investigation on the influence of minerals in co-firing applications in existing and developing systems, and their environmental impact on recycling to soils showed that biomass ashes were richer in calcium, silicon and alkali minerals and micronutrients such as Zn, Cu and Mn, in comparison to coal ashes and for coal biomass blends, composition and fusibility of the ashes varied among individual components. *Vamvuka and Kakaras* [40] concluded that co-firing processes using the alternative fuels considered up to 20 % would not impose significant limitations in the system operation or the management strategies of ashes.

The fusion characteristics stalks of capsicum, cotton and wheat showed that softening temperature, hemispherical temperature and fluid temperature were not affected by the

concentrations of each element and the ash temperature, and initial deformation temperature may be considered as an evaluation index of biomass ash fusion characteristic. From the results *Niu et al* [41] came to conclusion that, evaluation of the biomass ash fusion characteristic should not be based merely on the proportion of elements except initial deformation temperature, but the high-temperature molten material in biomass ash.

The physiochemical properties of ashes rice straw, pine sawdust and Chinese Parasol tree leaf at different ash temperature were investigated to analyse the ash content and composition. The results indicated that the ash content, composition, crystalline phase composition, surface morphology and ash fusibility were all closely related to ash temperatures. The analysis at 600°C ash temperature was regarded as the optimal for an exact determination of ash properties [42].

2.8 Co-firing of Biomass with Coal

The potential of co-firing biomass in power plants based on Brazilian coal and evaluated the technical limits of adding woody biomass to a boiler with a fluidized bed running on Brazilian coal was estimated. The results indicated that biomass should be available within a radius of around 120 km, which is equivalent to about 4,500,000 ha and only 0.4 % of this area would be required to feed a thermal plant of 600 MW with 30 % biomass [43].

Co-firing from the perspective of coal characteristics was considered and certain coal characteristics as more favourable to co-firing than others were identified. *Tillman* [44] also examined the coal characteristics issue as a function of the type of biomass being fired, the firing method, and post-combustion equipment. They concluded that there are some combinations of specific coals and specific biomass fuels that should not be used for combustion. Alternately there are some combinations that work out very favourably for the utility.

2.9 Regression Analysis on the basis of Proximate and Ultimate Analysis

A general correlation based on proximate analysis of biomass materials was introduced to estimate elemental composition. *Parikh et al* [45] derived the correlation using 200 data points and validated further for additional 50 data points. The results derived the following equations: for carbon content, $C = 0.637FC + 0.455VM$, for hydrogen content, $H = 0.052FC + 0.062VM$, and oxygen content, $O = 0.304FC + 0.476VM$ where, FC is fixed carbon content and VM is volatile matter content. The average absolute error of these correlations are 3.21 %, 4.79 %, 3.4 % and bias error of 0.21 %, 0.15 % and 0.49 % with respect to measured values of C, H and O respectively.

The applicability of the correlations with a special focus on Indian coals was evaluated. The model presented here was developed using analysis of 250 coal samples and its significance lies in involvement of all the major variables affecting the high heating value (HHV). *Majumder et al* [46] came to conclusion that the model $HHV = -0.03A - 0.11M + 0.33VM + 0.35FC$ where, A is ash content, M is moisture content, VM is volatile matter content and FC is fixed carbon content, appeared to be better than existing models.

Least squares regression analysis method was adapted for developing the correlations for estimating the calorific values from proximate analysis data of 20 different biomass samples. Regression coefficients of the correlations range from 0.829 to 0.898. Standard deviations of the heating values determined from 13 different correlations were between 0.4419 and 0.5280 [47]. The correlation based on ultimate analysis ($HHV = 0.2949C + 0.8250H$) has a mean absolute error (MAE) lower than 5 % and marginal mean bias error (MBE) at just 0.57 % which shows that it has a good HHV predictive capability. The other correlation which was based on

proximate analysis ($\text{HHV} = 0.1905\text{VM} + 0.2521\text{FC}$) is an useful companion correlation with low absolute MBE of 0.67 % [48].

About 250 published data with HHV ranging from 5.63 to 23.46 MJ/kg were used to develop correlations, and were analyzed for its forecasting errors. The selected linear and non-linear correlations were validated by using experimentally determined higher heating values of biomass [49].

2.10 Decentralized Power Generation

A group of 10-15 villages comprising of 3000 families was considered, for which one power station was planned. The power requirement for domestic work, irrigation, and small-scale industries in these villages was estimated to be around 20,000 kWh/day (7300 MWh/year) and calculations were carried out by *Kumar et al* [50]. The calculation results showed that approximately 44, 52 and 82 hectares of land are required for energy plantations with *Sida rhombifolia*, *Vinca rosea*, and *Cyperus* biomass species in order to ensure a perpetual supply of electricity for a group of 10–15 villages. For *Ocimum canum* and *Tridax procumbens*, approximately 650 and 1,270 hectares of land respectively are required to generate 20,000 kWh/day electricity [5].

2.11 Summary

Although lot of work has been done in the field of bio-energy, from the literature review it is vivid that there is lack of research in exploiting many agricultural biomass wastes for power generation which holds a significant share in renewable energy sources. Moreover, the knowledge about the fundamental properties of these biomass wastes like chemical compositions, calorific values, bulk densities and ash fusion temperatures are not complete. It is

observed that literature in context to co-firing of coal with biomass is limited and study on decentralised power generation for remote villages is the need of hour. Development of regression equations to predict gross calorific values on the basis of data from proximate and ultimate analyses is still in its initial stages and therefore, there is scope for further development in this area.

2.12 Objectives

The objectives of the present project work are as follows:

- a) Proximate analysis of different components such as leaf, stem, shell, pith coir, stalk and husk of some selected agriculture based biomass residues.
- b) Characterization of these biomass components on the basis of their gross calorific values.
- c) Characterization of coal mixed biomass components on the basis of their gross calorific values, and analysis of samples of coal and biomass mixed in different ratios.
- d) Determination of fusion temperatures of ashes obtained from some selected agricultural biomass residues.
- e) Ultimate analysis of some selected components of agricultural residues
- f) Developing regression equations to predict gross calorific values from proximate and ultimate analyses data of the biomass samples.
- g) Estimation of power generation potentials and land area requirements for the studied agricultural biomass species for decentralized power generation.

Chapter 3

EXPERIMENTAL WORK

- *Introduction*
- *Selection of Materials*
- *Proximate Analysis*
- *Calorific Value Determination*
- *Determination of Ash Fusion Temperatures*
- *Ultimate Analysis*
- *Bulk Density of the Selected Agricultural Residues*

3. EXPERIMENTAL WORK

3.1 Introduction

This chapter provides the details of the materials selected for this project work, and the experimental procedures to determine the fundamental properties of biomass species are explained. After the materials were selected, the samples were subjected to a series of characterisation tests i.e., proximate and ultimate analyses, determination of calorific value, bulk density and ash fusion temperatures.

3.2 Selection of Materials

For this project work, waste residues of six different types of agricultural residues were procured from local vicinity. The local and botanical names of the biomass species selected for the experimental work have been listed in Table 3.1. The components of these biomass species like leaf, pith, coir, shell, husk, etc. were removed separately. The residual components of these samples were dried in air in a cross ventilated room for 30 days till their moisture content attains equilibrium with that of the atmosphere. The air-dried biomass samples were ground into powders and processed for their proximate and ultimate analyses, and calorific value determination.

Table 3.1: Local and Botanical Names of Selected Biomass Species

Sl. No.	Local Names	Botanical Names	Family
1	Banana	<i>Musa acuminata</i>	<i>Musaceae</i>
2	Coconut	<i>Cocos nucifera</i>	<i>Areaceae</i>
3	Arecanut Palm	<i>Areca catechu</i>	<i>Areaceae</i>
4	Rice	<i>Oryza sativa</i>	<i>Gramineae</i>
5	Wheat	<i>Triticum aestivum</i>	<i>Poaceae</i>
6	Palm	<i>Borassus flabellifer</i>	<i>Areaceae</i>

3.3 Proximate Analysis

Proximate analysis is a method for the qualitative analysis of different components in a mixture and gives a rough idea of its chemical composition. The analysis was carried out on the samples ground to -72 mesh size by standard method. In other words, the size of powder should be so small that it can easily pass through a screen having a mesh of 72 openings per 1 square inch. Proximate analysis is the most often used analysis for characterizing a fuel in connection with their utilization. The proximate analysis of the sample was determined in accordance with the Indian Standard Method [51]. It consists of the determination of the followings:

- i. Percentage of moisture content
- ii. Percentage of ash content
- iii. Percentage of volatile matter
- iv. Percentage of fixed carbon content

3.3.1 Determination of moisture content

The moisture content is an undesirable constituent in the carbonaceous materials. It unnecessarily increases the weight of the carbonaceous material and increases energy consumption during its combustion in a boiler. The moisture content is expressed as either dry basis or wet basis. In wet basis, the combined content of water, ash and ash free matter is considered whereas in dry basis, only ash and ash free matter is expressed as weight percentage. As the content of moisture is a determining factor for selection of a biomass fuel, the basis on which moisture is determined must be always mentioned [52].

One gram of air dried biomass specimens of -72 mesh size was taken in borosil glass crucible and heated at a temperature of $105 \pm 5^\circ\text{C}$ for one hour in an air oven. The crucible was then taken out from the oven and was cooled to room temperature in a desiccator. The weight loss in the material was measured by using an electronic balance. The percentage loss in weight was calculated which gives the percentage moisture content in the sample [51].

$$\text{Percentage of moisture content} = \frac{\text{Wt. loss} \times 100}{\text{Initial wt. of sample}} \quad (3.1)$$

3.3.2 Determination of ash content

Ash is the residual inorganic material accumulated after complete combustion of any carbonaceous material. The chemical constituents of ash in general are Al_2O_3 , SiO_3 , K_2O , TiO_2 , Na_2O_3 , carbonates, silicates etc. The elements Al_2O_3 and SiO_3 constitute around 90 % of the total ash weight.

One gram sample of the selected specimen of -72 mesh size was taken in a shallow silica disc and kept in a muffle furnace maintained at the temperature of $775 \pm 25^{\circ}\text{C}$. The materials were heated at this temperature for about half an hour or till complete burning. The weight of the residue incurred was recorded by using an electronic balance. The percentage of ash content in the sample was calculated by using the formula [51]:

$$\text{Wt. \% of ash content} = \frac{\text{Wt. of residue obtained}}{\text{Initial wt. of sample}} \times 100 \quad (3.2)$$

3.3.3 Determination of volatile matter

Volatile matters are the products exclusive of moisture given off by the specimen when heated under high temperatures in the absence of air. It is a mixture of various gases like CO, CO₂, H₂S, hydrocarbons, etc. It also has got some energy value. The implicit knowledge of volatile matter can be used to establish rank of coals, to indicate coke yields on carbonization process and to establish burning characteristics. Char formed by combustion of materials are affected by volatile matter. The lower the volatile matter, the higher will be the char formation. Biomass usually has higher content of volatile matter as compared to coals which may go up to 80 % [52].

One gram each of -72 mesh size air dried powder of the selected sample was taken in a cylindrical crucible made up of silica. The crucibles were covered from the top with the help of silica lids. The crucibles were then placed in a muffle furnace which was maintained at the temperature of $925 \pm 5^{\circ}\text{C}$. After 7 minutes of soak time, crucibles were taken out from the furnace and cooled in air. After devolatilising, the samples were weighed in an electronics

balance and the percentage of weight loss was calculated. The percentage of volatile matter in the sample was determined by using the following formula [51]:

$$\text{Wt. \% of volatile matter} = \frac{\text{Wt. loss}}{\text{Initial wt. of the sample}} - \% \text{ of moisture content} \quad (3.3)$$

The accuracy of measurement of temperature in the muffle furnace was within $\pm 5^\circ\text{C}$ with a resolution of 1°C and the furnace can be safely operated in the range of $0-1000^\circ\text{C}$.

3.3.4 Determination of fixed carbon content

Fixed carbon is the solid combustible residue that remains after a coal particle is heated and the volatile matter is expelled. The fixed carbon content of any fuel is determined by subtracting the sum of percentages of moisture, volatile matter, and ash in a sample from 100. The fixed carbon content of the above selected sample were calculated as [51]:

$$\begin{aligned} \text{Fixed carbon content (wt. \%)} \\ = 100 - \text{wt. \% of (moisture content + ash content} \\ + \text{volatile matter)} \end{aligned} \quad (3.4)$$

3.4 Calorific Value Determination

Calorific value is the amount of energy per unit mass liberated upon complete combustion in presence of oxygen. It is a crucial criterion in estimating the quality of a material for its better utilization in generation of electricity as calorific values is an indication of the energy chemically bound in the material. The design and control of combustor strongly reckons on the energy value of carbonaceous materials. It is conventionally measured by using a bomb calorimeter and expressed in kcal/kg or MJ/kg.

The calorific value of a substance can be classified as:

i. *Gross calorific value:*

It is also known as higher heating value. Water vapour is produced when the hydrogen present in the fuel reacts with oxygen during the combustion process. The condensation of this water vapour to liquid water inside the bomb takes place at the condensation temperature and it will liberate latent energy. This latent heat of water is an addition to the energy liberated by unit mass of fuel and the measured value is known as gross calorific value.

ii. *Net calorific value:*

It is defined as the amount of heat generated when a unit weight of the fuel is completely burnt and water vapour bequeaths with combustion products without being condensed. The latent heat of vaporization of water in the reaction products is not recovered. Net calorific value is calculated by subtracting the latent heat of vaporization of water from the gross calorific value and it is estimated that net calorific value is 90 % of gross calorific value. Thus, it is also known as lower heating value.

The gross calorific values of the biomass samples were measured by using an Oxygen Bomb Calorimeter as per Indian Standard Method [53]. The major components of the calorimeter are shown in Fig. 3.1.

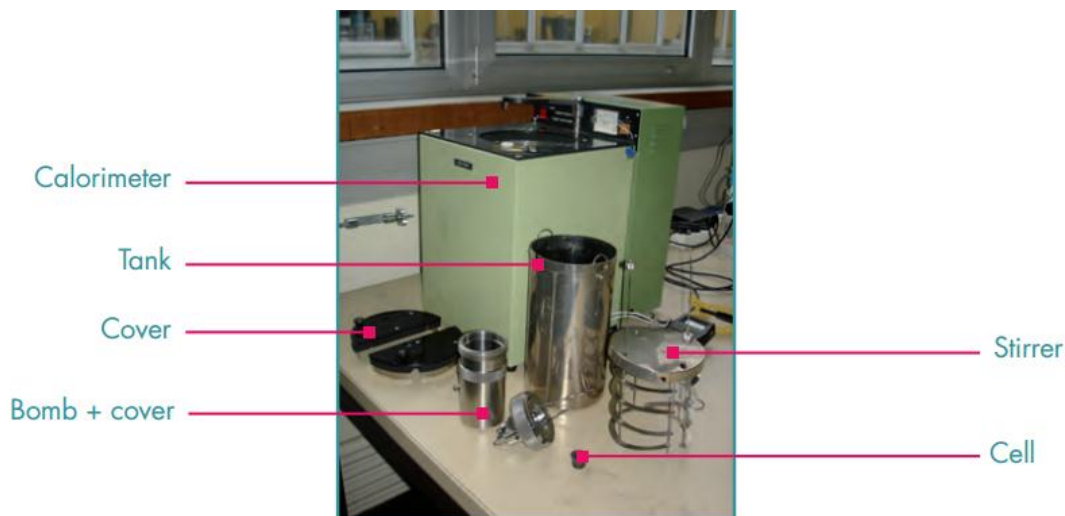


Fig 3.1: Bomb Calorimeter

One gram of oven dried briquetted sample was taken in a nicron crucible and a 15 cm long cotton thread was placed over the sample in the crucible to initiate the ignition. The electrodes of the calorimeter were connected by a nicron fuse wire. The bomb was filled up with oxygen gas at a pressure of 25 to 30 atm. About two litres of water was taken in the stainless steel vessel of the calorimeter and the bomb containing the sample was immersed inside it. The calorimeter was switched on and the water was stirred to homogenize the temperature. The rise in the temperature of water was recorded after every one minute time interval and by using the following formula gross calorific value of the sample was calculated [53].

$$GCV = \left[\frac{W.E. \times \Delta T}{w} \right] - (\text{heat released by cotton thread} + \text{heat released by fused wire}) \quad (3.5)$$

where, W.E. = water equivalent of apparatus = 1.987 kcal/°C

ΔT = maximum rise in temperature in °C

w = initial weight of the dried sample in gram

Equation 3.5 gives the gross calorific value in kcal/kg, which is converted to SI unit i.e., MJ/kg by multiplying it with a factor 0.004184. The oxygen bomb calorimeter used can be safely operated in the measurement of calorific value up to about 34.31 MJ/kg and the accuracy in the measurement is about $\pm 2\%$. The resolution of the temperature scale present in the calorimeter is 0.01°C and an accuracy of $\pm 0.02^\circ\text{C}$ with the measuring range of $0\text{--}10^\circ\text{C}$.

3.5 Determination of Ash Fusion Temperatures

It is the temperature at which a test cubic sample made from ash obtained from combustion of a carbonaceous material will begin to deform or fuse into an indistinct form. Ash fusion temperature of an ash residue is a key factor in determining the potential of a fuel for power generation at boiler temperature. If the fusion temperature of a fuel is lower than boiler operating temperature, it produces slagging and fouling in the boiler. Clinker formation by combustion of coal or biomass is undesirable in boilers and hence, it poses mechanical threats. Hence, an adequate knowledge of ash fusion temperatures becomes pre-requisite for furnace designing.

Ash fusion temperature involves monitoring of four different temperatures which are as follows:

- i. *Initial deformation temperature (IDT)*: It is the temperature at which the corners of the sample just starts to deform.
- ii. *Softening temperature (ST)*: It is the temperature at which the sample starts shrinking.

- iii. *Hemispherical temperature (HT)*: It is the temperature at which the sample becomes hemispherical in shape.
- iv. *Fluid temperature (FT)*: It is the temperature at which the sample melts and spreads over the surface [54].

The determination of ash fusion temperatures of biomass was conducted in accordance to a German Standard Test [55] in which the selected biomass samples were first converted to ash by heating them to a maximum temperature of 700°C in the muffle furnace. Around 3-4 mg of the ash sample was processed to a cubic shape of each side 3 mm and kept in a Leitz high temperature microscope (Make - Leica, Wetzlar, Germany as shown in Fig 3.2) which was heated at a rate of $8^{\circ}\text{C min}^{-1}$ up to the fluid temperature. Leitz high temperature microscope used in the measurement of ash fusion temperatures was capable of recording the temperatures up to 1600°C . It has an accuracy of $\pm 5^{\circ}\text{C}$ and resolution of 1°C .



Fig 3.2: Leitz Heating Microscope

During the course of heating, the physical changes occurring in the cubic samples were observed after a regular interval of time. The temperature at which the cubic ash sample started to deform was recorded as initial deformation temperature of the sample. The heating was further continued and the temperature at which the rounding of the corners and shrinkage in the sample took place was noted down as softening temperature of the ash sample. Heating further changed the cubic ash sample in to hemispherical shape and the corresponding temperature is the hemispherical temperature of the concerned sample. Again heating was further continued and the temperature at which the cubic ash sample completely melts and spreads over the surface was noted down as fluid temperature of the ash sample. The shapes of ash sample at various ash fusion temperatures are shown in Fig. 3.3.

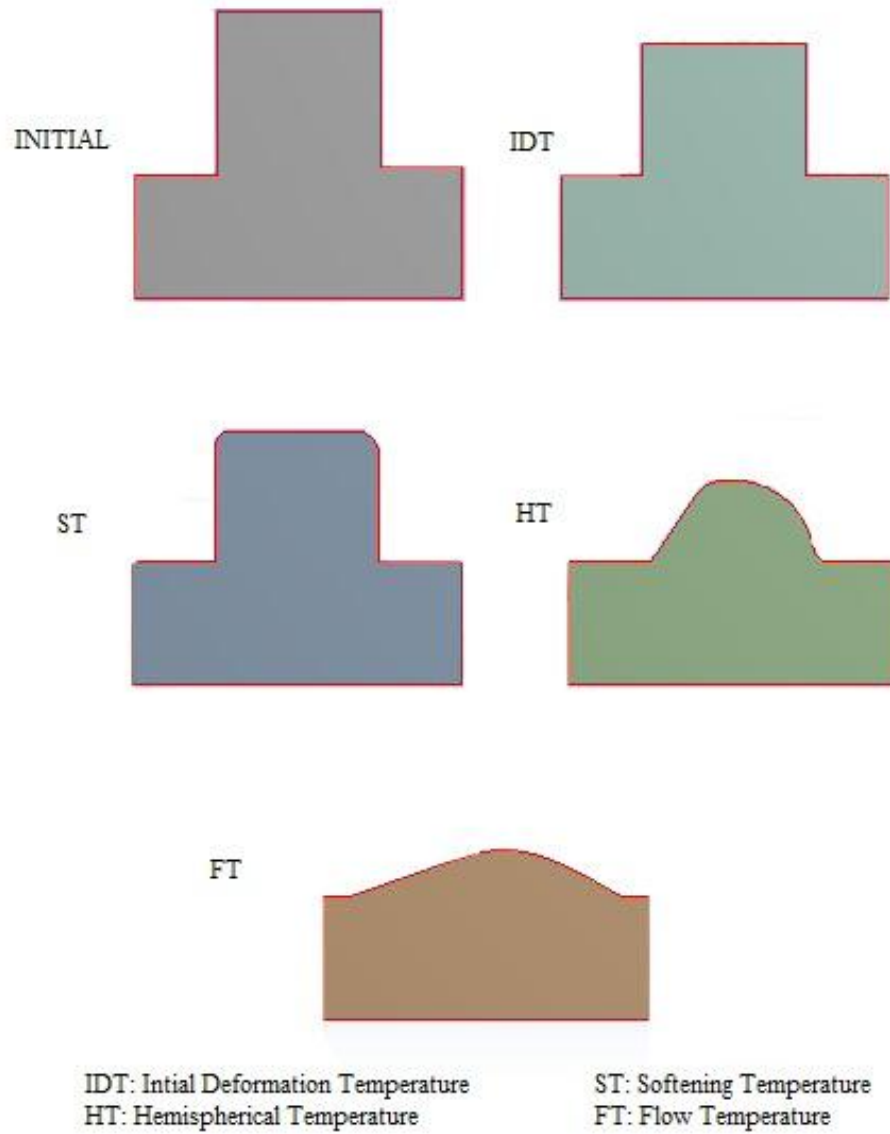


Fig 3.3: Different Ash Fusion Temperatures

3.6 Ultimate Analysis

The ultimate analysis gives an idea about the elemental composition of the carbonaceous materials. The weight percentage of various elements like carbon (C), hydrogen (H), nitrogen (N), oxygen (O) and sulphur (S) in a fuel can be determined quantitatively by this analysis. The knowledge of carbon (C) and hydrogen (H) is very vital in determining the calorific value of the fuel. The calorific value of carbon is around 33.77 MJ/kg whereas the energy value of hydrogen is around 144.21 MJ/kg i.e., the calorific value of hydrogen is more than four times to that of carbon.

The ultimate analyses for carbon (C), hydrogen (H), nitrogen (N) and oxygen (O) contents in some of the selected agricultural residues were determined by CHN analyser at Sophisticated Analytical Instrumentation Facility, Panjab University, Chandigarh, India.

3.7 Bulk Density of the Selected Agricultural Residues

The bulk density of the selected biomass species were determined by using a cubic steel container of each side 60 mm. The steel container was completely filled with the biomass sample and the weight of the sample was recorded by using an electronic balance. The bulk density was calculated by dividing the weight of the biomass in the container by the volume of the container.

3.8 Uncertainty of Measurement

Uncertainty of measurement is the imperfection inherent in the results of measurement. In order to quantify an uncertainty, two numbers are required, one is width of margin or interval and other is confidence level. Confidence level states how sure we are that the true value is within that margin.

3.8.1 Standard Deviation

Standard deviation is a measure that is used to quantify the amount of variation or spread of a set of data values. The standard deviation of a set of numbers tells us about how different readings typically are from the average of the set. The symbol σ_{n-1} denotes the standard deviation and the standard deviation for a series of n measurements can be estimated by using the following:

$$\sigma_{n-1} = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)}} \quad (3.6)$$

where, x_i = result of the i th measurement, and

\bar{x} = arithmetic mean of the n results considered.

3.8.2 Propagation of Uncertainty

The propagation of uncertainty is applied to combine measurements with the assumptions that as measurements are combined, uncertainty increases and hence the uncertainty propagates through the calculations.

When adding two measurements, the uncertainty in the final measurement is the sum of the uncertainties in the original measurements and is calculated as

$$(A \pm \delta A) + (B \pm \delta B) = (A + B) \pm (\delta A + \delta B) \quad (3.7)$$

Similarly, when subtracting two measurements, the uncertainty is again equal to the sum of the uncertainties in the original measurements and is given by:

$$(A \pm \delta A) - (B \pm \delta B) = (A - B) \pm (\delta A + \delta B) \quad (3.8)$$

When multiplying two measurements, the uncertainty in the final measurement is found by summing the percentage uncertainties of the original measurements and then multiplying that sum by the product of the measured values and is expressed as

$$(A \pm \delta A) \times (B \pm \delta B) = (AB) \left[1 \pm \left(\frac{\delta A}{A} + \frac{\delta B}{B} \right) \right] \quad (3.9)$$

When dividing two measurements, the uncertainty in the final measurement is found by summing up the percentage uncertainties of the original measurements and then multiplying that sum by the quotient of the measured values and is given as

$$\frac{(A \pm \delta A)}{(B \pm \delta B)} = \left(\frac{A}{B} \right) \left[1 \pm \left(\frac{\delta A}{A} + \frac{\delta B}{B} \right) \right] \quad (3.10)$$

Chapter 4

REGRESSION ANALYSIS

- *Introduction*
- *Regression Analysis*
- *Linear Regression Analysis*
- *Parameters of Regression Analysis*
- *Evaluation of Errors*

4. REGRESSION ANALYSIS

4.1 Introduction

Calorific value is one of the most significant aspects in the selection of a solid fuel and the designing of the boiler assisting biomass combustion depends upon the calorific value of the biomass. It can be determined by both experimental methods as well as analytical methods. The experimental methods are already discussed in the previous chapter. The calorific value is determined experimentally by a calorimeter which needs special skills to operate and consumes a lot of time [56]. But in case of analytical method, regression equations were developed to determine gross calorific value (GCV) from the data of proximate and ultimate analyses without conducting any fresh experiments. Considering proximate analysis, regression equation for GCV has been expressed as the function of variables such as moisture content, ash content, volatile matter content and fixed carbon content [57]. Similarly, from the data of ultimate analysis, GCV has been expressed as the function of variables such as carbon, hydrogen, oxygen and nitrogen [58]. For this project work, the above expressions have been established on the basis of regression analysis with the help of Statistica software of version 9.1.

4.2 Regression Analysis

Regression analysis is a statistical technique to analyze the variables and to determine the relationship between the dependent and independent variables. In general, it is used to predict and forecast the regression function. Usually, the known values of dependent and independent variables are utilized to develop an equation called regression equation [59].

On the basis of the number of independent variables, regression analysis can be classified into two broad categories i.e., Simple Regression Analysis (SRA) and Multiple Regression

Analysis (MRA). There is only one independent variable in SRA whereas MRA has more than one. On the basis of the relationship between dependent and independent variables, regression analysis can be classified into two groups such as, Linear Regression Analysis and Nonlinear Regression Analysis. The relationship between dependent and independent variables can be direct or inverse. Direct relationship shows increase in dependent variable with the increase in independent variable displaying a positive slope in the graph. On the other hand in inverse relationship, the dependent variable decreases with the increase in independent variable and the slope is negative [60].

4.3 Linear Regression Analysis

Linear regression analysis is a statistical approximation in which a dependent or explained variable is linearly related to one or more independent or explanatory variables. In linear regression, the linear prediction functions are used to model the data and using this, the unknown model parameters are estimated. The least square approach is most widely used to fit linear regression models.

4.3.1 Simple linear regression analysis

Simple Linear Regression Analysis (SLRA) is a statistical technique which is used to estimate the linear relationship between the dependent variable and the single independent variable. Mathematically, it is expressed as [61]:

$$Y = a_0 + a_1 X \quad (4.1)$$

where, Y = dependent or explained variable,

X = independent or explanatory variable and

$a_0, a_1 = \text{constant parameters.}$

4.3.2 Multiple linear regression analysis

Multiple Linear Regression Analysis (MLRA) is used to approximate the relationship between two or more independent variables and one dependent variable by fitting a linear equation. MLRA can be expressed mathematically as shown in Equation 4.2 [60].

$$Y = a_0 + a_1X_1 + a_2X_2 + \dots + a_nX_n \quad (4.2)$$

where $a_0, a_1, a_2 \dots a_n$ are constant parameters.

4.4 Parameters of Regression Analysis

4.4.1 Standard error of estimate

The standard error of the estimate is a measure of the accuracy and reliability of the predicted equations. It has properties analogous to those of standard deviation. The standard deviation gives the dispersion of a set of observations about their mean whereas the standard error of estimate measures the variability of the observed values around the regression line. The standard error of estimate is expressed by the following formula [60]:

$$S = \sqrt{\frac{\sum(Y - \bar{Y})^2}{N - k - 1}} \quad (4.3)$$

where, Y = sample values of dependent variable,

\bar{Y} = corresponding estimated values from the regression equation,

N = number of data points in the sample, and

k = number of independent variables.

4.4.2 Coefficient of determination

In regression analysis, the coefficient of determination is a statistical measure of how well the regression line approximates the real data points. It provides information about the goodness of fit of a model. It is a statistic used in the context of statistical models whose main purpose is either the prediction of future outcomes or the testing of hypotheses, on the basis of other related information. It provides a measure of how well observed outcomes are replicated by the model, as the proportion of total variation of outcomes explained by the model. It is denoted by R^2 . Mathematically,

$$R^2 = 1 - \frac{\sum(Y - \hat{Y})^2}{\sum(Y - \bar{Y})^2} \quad (4.4)$$

where, $\sum(Y - \hat{Y})^2$ = variation of the Y value around the regression line

$\sum(Y - \bar{Y})^2$ = variation of Y values around their own mean

The higher value of R^2 suggests that the model developed is more useful and it takes values between 0 and 1. When R^2 takes the value 1, this implies that every data point lies on the regression line, suggesting perfect correlation between dependent and independent variables. On the other hand, when R^2 takes the value 0, no data point lies on the regression line indicating no correlation between dependent and independent variables [60].

4.4.3 Coefficient of correlation

The coefficient of correlation measures the strength and direction of a linear relationship between two variables. It is denoted by R. It is also called Pearson product-moment correlation coefficient. It takes values between -1 and $+1$, where 1 is total positive correlation, 0 is no correlation, and -1 is total negative correlation. As compared to R^2 the coefficient of correlation is more difficult to interpret, it is usually considered for the evaluation of regression equations [60].

4.5 Evaluation of Errors

The evaluation of error is essential as it indicates the goodness of the developed model. To evaluate the accuracy of the developed equations, two statistical parameters, i.e., average bias error (ABE) and average absolute error (AAE) were used [62]. Mathematically,

$$ABE = \frac{1}{N} \sum_{i=1}^N \left[\frac{\text{Predicted value} - \text{Measured value}}{\text{Measured value}} \right] \times 100\% \quad (4.5)$$

$$AAE = \frac{1}{N} \sum_{i=1}^N \left| \frac{\text{Predicted value} - \text{Measured value}}{\text{Measured value}} \right| \times 100\% \quad (4.6)$$

where, N = number of data points.

AAE quantifies how close the predicted values are to the experimental values in which lower AAE indicates higher accuracy. For ABE, a positive value indicates an overall over-estimation while a negative value indicates an overall under-estimation. The smaller the value of ABE, the smaller the bias of the correlation [48].

Chapter 5

RESULTS AND DISCUSSION

- *Introduction*
- *Chemical Compositions of the Studied Biomass Species*
- *Calorific Value*
- *Ash Fusion Temperatures*
- *Co-firing of Mixed Briquettes of Coal-Selected Biomass Species*
- *Bulk Density*
- *Regression Analysis*
- *An Approach for Decentralized Power Generation and Energy Plantation Structure*

5. RESULTS AND DISCUSSION

5.1 Introduction

The results obtained from the proximate and ultimate analyses, bulk densities, calorific values and ash fusion temperatures of selected agricultural residues have been outlined in Tables 5.1-5.7. The regression analysis has also been done on the basis of proximate and ultimate analyses data and the equations developed for gross calorific values are shown in Tables 5.13 and 5.14.

5.2 Chemical Compositions of the Studied Biomass Species

5.2.1 Proximate analysis

The knowledge of the proximate analysis of the selected agricultural residues is vital as it provides an approximate idea about the energy values and extent of pollutant emission during their combustion. The freshly cut biomass species contains a large amount of free moisture which needs to be removed in order to decrease the cost of transportation and increase the calorific value. The proximate analysis of different components of the selected biomass species are presented in Table 5.1.

From Table 5.1, it can be observed that moisture content of palm leaf is highest (i.e., 12 wt.%) among all the selected biomass species whereas the stem of banana plant exhibited lowest moisture content (i.e., 5 wt.%). The presence of high moisture content in the biomass is expected to reduce the overall thermal efficiency and increase the energy consumption during combustion in boiler operation. Moreover, the transportation becomes less efficient and the energy value of biomass with high moisture content is low. Hence, the moisture content of the biomass should be removed before utilizing it for power generation. Table 5.1 shows that the ash content in the

palm shell is the lowest (i.e., 3 wt.%) and rice stalk has the highest (i.e., 33 wt.%) ash content among all the agricultural residues taken for this project work. The efficiency of the boiler is affected by high ash content and also tends to causes clinkering and slagging problems in boiler. In comparison to coals, the ash contents of the studied biomass species were found to be much lower. This is highly advantages in the regard that the ash generation/accumulation near the thermal power plants will drastically reduce. So this will definitely help in reducing the atmospheric pollution from thermal power plant.

It is also apparent from Table 5.1 that the volatile matter of all the 12 studied biomass species ranges between 62-73 wt.%, with rice stalk being an exception having volatile matter as low as 45 wt.%. The shells of coconut and palm has the highest volatile matter content (72-73 wt.%) among the selected biomass samples. Others were having the volatile matter contents in the range 62-67 wt.%. The volatile matter is a gaseous mixture of many gases like SO_x , NO_x , C_nH_m , etc. and thus contributes to the energy value of biomass. It is quite clear from the volatile matter results that huge amount of gases will be generated inside the boilers during the utilization of biomasses in appreciable amounts in them. Hence, special attention needs to be given in designing of boilers for the utilization of biomasses.

It is observed from this table, the stem of banana has the highest fixed carbon content and the shell of coconut has the lowest, which are around 20 wt.% and 9 wt.% respectively. Fixed carbon content in the solid fuels ensures the availability of carbon in the boilers for combustion. In general, the solid fuels having higher fixed carbon content generates higher amount of heat energy inside the boilers. Fixed carbon content differs from the total carbon content in that the total carbon content is the sum of carbon content of fixed carbon content and volatile matter.

Table 5.1: Proximate Analysis of Different Components of Studied Biomass Species

Samples	Proximate analysis (wt.%, dry basis)			
	Moisture content	Ash content	Volatile matter	Fixed carbon content
Banana				
Leaf	6	17	63	14
Stem	5	10	65	20
Coconut				
Leaf	6	16	67	11
Shell	9	9	73	9
Pith	8	11	64	17
Arecanut				
Leaf	8	16	66	10
Coir	9	9	64	18
Wheat				
Stalk	11	6	65	18
Palm				
Leaf	12	6	65	17
Shell	8	3	72	17
Rice				
Stalk	10	33	45	12
Husk	7	19	62	12

5.2.2 Ultimate analysis

The ultimate analysis gives an idea about the chemical elements (carbon, hydrogen, nitrogen, sulphur, and oxygen) and ash content of a carbonaceous material. This analysis provides the composition of the sample which is important to define the energy content, and to determine how clean and efficient the sample is for the purpose it is used for. The results obtained from the ultimate analysis of nine different samples of selected agricultural residues have been reported in Table 5.2. From the ultimate analysis results, one can determine gross calorific value of the concerned solid fuel by using the Dulong and Petit's formula which is as follows [63]:

$$GCV = \frac{1}{100} [8080 \times C + 34500 \left(H - \frac{O}{8} \right) + 2200 \times S] \quad (5.1)$$

where, C, H, O and S are the weight percentage of carbon, hydrogen, oxygen and sulphur content contents in the sample.

The carbon and hydrogen contents of coconut leaf have been found out to be the highest among all the studied biomass species i.e., 45.456 and 5.656 wt.% respectively as evident from Table 5.2. On the other hand, the carbon and hydrogen contents of the rice stalk has been reported to be the lowest i.e., 24.826 and 3.381 wt.% respectively. Rest of the samples have carbon and hydrogen contents in the range 35-44 wt.% and 3.3-5.5 wt.% respectively.

The oxygen content of coconut pith has been found out to be 40.958 wt.% which is the highest among all the selected samples and rice stalk with oxygen content of 21.310 wt.% has the lowest. The other components have oxygen content in the range 31-39 wt.%. The oxygen present in the sample helps in its combustion in the boiler. The table also shows that the nitrogen content in the studied samples is in the range 0 - 4.725 wt.%, with wheat stalk being reported to have the

highest value. The nitrogen contents of both shell and pith of coconut were found to be zero which shows that nitrogen content barely affects the gross calorific value.

Table 5.2: Ultimate Analysis of Different Components of Studied Biomass Species

Samples	Ultimate analysis (wt. %, dry basis)			
	Carbon	Hydrogen	Oxygen	Nitrogen
Banana				
Stem	35.351	4.162	36.334	1.142
Coconut				
Leaf	45.456	5.656	37.146	0.839
Shell	43.996	4.799	38.699	0
Pith	37.497	4.605	40.958	0
Arecanut				
Leaf	41.755	5.499	34.725	2.240
Wheat				
Stalk	37.899	5.413	38.988	4.725
Palm				
Leaf	43.598	5.381	37.366	1.200
Rice				
Stalk	24.826	3.381	21.310	1.687
Husk	37.357	5.269	31.463	2.208

5.3 Calorific Value

Power generation potential of any energy source can be estimated on the basis of its calorific value. The knowledge of calorific value helps in depicting the quality of fuel required for power production. That is why the calorific value of any fuel source is an important criterion for its selection in power plants. The results obtained for the gross calorific values of the studied biomass samples have been listed in Table 5.3.

It is evident from Table 5.3 that the leaf of coconut has the highest calorific value and the stalk of rice has the lowest among all the selected biomass samples which are 19.763 MJ/kg and 14.242 MJ/kg respectively. It is quite clear from the literature that the carbon and hydrogen are the major elements that affect the gross calorific value. The variations in gross calorific value of the studied biomass species, as can be seen in Table 5.3, are undoubtedly related to the combined effects of their carbon and hydrogen contents. For example, it can be seen in Table 5.2 that the highest gross calorific value of the coconut leaf is due to its highest carbon and hydrogen contents, and the lowest gross calorific value of rice stalk is due to its lowest carbon and hydrogen contents. In addition, the carbon and hydrogen contents give an idea about the availability of combustibles in a boiler.

Table 5.3: Calorific Values of Different Components of Studied Biomass Species

Sl. No	Sample	Gross Calorific Value (MJ/kg)
1	Banana Leaf	17.406
2	Banana Stem	17.523
3	Coconut Leaf	19.763
4	Coconut Shell	18.898
5	Coconut Pith	17.124
6	Arecanut Leaf	17.879
7	Arecanut Coir	16.565
8	Wheat Stalk	16.605
9	Palm Leaf	17.752
10	Palm Shell	18.155
11	Rice Stalk	14.242
12	Rice Husk	16.872

5.4 Ash Fusion Temperatures

Ash fusion temperatures (AFTs) of six selected agricultural residues viz., stalks of rice and wheat, rice husk, coconut pith and leaves of arecanut and palm were measured. The results obtained for the four fusion temperatures (i.e., initial deformation temperature (IDT), softening temperature (ST), hemispherical temperature (HT) and flow temperature (FT)) of the studied biomass species have been tabulated in Table 5.4.

From the AFT results listed in Table 5.4, it is evident that IDT and ST values of the studied ash samples are in the range 938-1137 °C and 1083-1211 °C respectively, whereas the values of HT and FT are in the range of 1151-1281 °C and 1194-1339 °C respectively. Among all types of fusion temperatures, the lowest is observed to be 938 °C (i.e., for the stalk of rice) which is substantially above the normal boiler temperature (i.e., 800 °C). This gives an indication that all the selected biomass samples can be used for combustion in boiler safely without clinker formation.

AFT is one of the important criteria to be taken in consideration while selecting a solid fuel for combustion in boilers. AFTs give an idea about the possibility of clinker formation inside the boilers and other ash related problems like damage of the refractory walls. Out of the four characteristics ash fusion temperatures, the value of initial deformation temperature is considered to be the most important in selection of solid fuels for application in boilers.

Table 5.4: Ash Fusion Temperatures of Different Biomass Samples

Biomass samples	Ash fusion temperatures, °C			
	IDT	ST	HT	FT
Rice Stalk	938	1096	1198	1242
Wheat Stalk	996	1083	1151	1265
Rice Husk	1075	1211	1281	1339
Coconut Pith	978	1086	1156	1194
Arecanut leaf	1058	1128	1246	1274
Palm Leaf	1137	1192	1227	1254

5.5 Analysis of Co-firing Potentials of Mixed Briquettes of Coal-Selected Biomass Species

The chemical composition and energy values of mixed briquettes of coal-rice husk and coal-palm leaf of different ratios have been tabulated in Tables 5.5 and 5.6 respectively. From these tables, it is vivid that there is decrease in ash content and increase in content of volatile matter for both the coal-biomass mixed samples in contrast to the biomass free coal sample (i.e., coal: biomass = 100:0) as the percentage of biomass increases in the briquettes. It is evident from the tables that the mixing of biomass with coal decreases ash content substantially which is an important criterion in selection of solid fuels as low ash content fuel ensures smooth boiler operation. Hence, the use of biomass with coal in co-firing process should be considered as it can help in reduction of emission and bed agglomeration problems.

From the same tables it is evident that, the blending of coal with biomass also affects the calorific value. In case of coal and rice husk mixed briquette sample, the calorific value increased when the briquette sample was taken in the ratio 90:10 but it decreased when the briquette sample was taken in the ratio 85:15. On the other hand, all the coal and palm leaf mixed briquette samples exhibited an increase in calorific value with the increase in percentage of palm leaf in the briquette samples. The briquette sample with coal and palm leaf mixed in the ratio 85:15 was found to have the highest calorific value (i.e., 18.213 MJ/kg) among all the biomass samples studied in different ratios for analysing co-firing potentials.

Table 5.5: Proximate Analysis and Gross Calorific Values of Coal-Biomass (Rice husk) Mixed Briquette in Different Ratios

Ratio (coal : biomass)	Proximate analysis (wt.% dry basis)				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	5	38	22	35	17.292
90 : 10	6	30	27	37	17.624
85 : 15	4	28	32	36	17.016

Table 5.6: Proximate Analysis and Gross Calorific Values of Coal-Biomass (Palm leaf) Mixed Briquette in Different Ratios

Ratio (coal : biomass)	Proximate analysis (wt.% dry basis)				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	5	38	22	35	17.292
90 : 10	6	29	28	37	17.672
85 : 15	7	28	30	35	18.213

5.6 Bulk Density

The study of bulk density of solid fuel is important for its utilization in power generation through the boiler route as it gives an idea about the amount of solid carbonaceous material to be accommodated in a given volume of the boiler. Higher bulk density facilitates the accommodation of large amount of carbonaceous material in a given volume of the boiler. Not only this, higher bulk densities of solid fuels reduces their cost of transportation and handling.

The bulk density of rice husk has been found out to be the highest (i.e., 336.257 kg/m³) and that of palm shell is the lowest (i.e., 108.673 kg/m³) among all the studied biomass samples as seen from Table 5.7. Other biomass samples have been found to be in the range 120 to 297 kg/m³.

Table 5.7: Bulk Density of Selected Biomass Species

Sl. No	Sample	Bulk Density (kg/m^3)
1	Banana Leaf	175.925
2	Banana Stem	120.370
3	Coconut Leaf	296.290
4	Coconut Shell	164.814
5	Coconut Pith	173.611
6	Arecanut Leaf	248.015
7	Arecanut Coir	187.982
8	Wheat Stalk	174.359
9	Palm Leaf	223.784
10	Palm Shell	108.673
11	Rice Stalk	156.364
12	Rice Husk	336.257

5.7 Determination of Uncertainty

Uncertainty in measurements of proximate analyses, gross calorific values and bulk density have been calculated and presented in Tables 5.8 – 5.12. Considering all the three readings recorded from the experiments for all the properties, uncertainties in measurements were calculated.

Banana stem has been taken as sample for showing the calculation of uncertainty in measurement of moisture content as shown below.

Three readings of moisture content in wt. % = 5, 5 and 6.

For these reading, mean (μ) and standard deviation (σ) are calculated as

$$\mu = \frac{(5+5+6)}{3} = 5.33 \approx 5$$

$$\sigma = \sqrt{\left(\frac{(5-5)^2 + (5-5)^2 + (5-6)^2}{(3-1)} \right)} = \sqrt{0.5}$$

Considering 95 % confidence level, moisture content in banana stem is found to be $5 \pm 2 \times \sqrt{0.5} = 5 \pm 1.41$ wt. %.

The procedure of calculation of uncertainty in measurement of gross calorific value (GCV) of banana stem was different from that followed in the previous paragraph as GCV involves ratio of two variable i.e. maximum rise in temperature inside bomb calorimeter (say, A) and weight of the selected sample (say, B). A sample calculation for determining uncertainty in measurement of GCV of banana stem has been present.

Three readings of weight of the sample in g = 0.71, 0.73 and 0.75.

Corresponding maximum rise in temperatures in $^{\circ}\text{C}$ = 1.53, 1.54 and 1.55.

Mean (μ) and standard deviation (σ) of these two sets of data were calculated as,

$$\mu_B = \frac{(0.71+0.73+0.75)}{3} = 0.73 \text{ g.}$$

$$\sigma_B = \sqrt{\left(\frac{(0.73 - 0.71)^2 + (0.73 - 0.73)^2 + (0.73 - 0.75)^2}{(3-1)} \right)} = 0.02 \text{ g.}$$

$$\mu_A = \frac{(1.53 + 1.54 + 1.55)}{3} = 1.54 ^\circ\text{C.}$$

$$\sigma_A = \sqrt{\left(\frac{(1.54 - 1.53)^2 + (1.54 - 1.54)^2 + (1.54 - 1.55)^2}{(3-1)} \right)} = 0.01 ^\circ\text{C.}$$

Considering 95 % confidence level,

$$A \pm \delta A = \mu_A \pm 2 \times \sigma_A = 1.54 \pm 2 \times 0.01 = 1.54 \pm 0.02 ^\circ\text{C.}$$

$$B \pm \delta B = \mu_B \pm 2 \times \sigma_B = 0.73 \pm 2 \times 0.02 = 0.73 \pm 0.04 ^\circ\text{C.}$$

Further, using Eq 3.5 and 3.10 uncertainty in measurement of GCV was calculated as follows,

$$\begin{aligned} GCV &= W.E. \times \left(\frac{(A \pm \delta A)}{(B \pm \delta B)} \right) \\ &= 1987 \times \left(\frac{A}{B} \right) \times \left[1 \pm \left(\frac{\delta A}{A} + \frac{\delta B}{B} \right) \right] \\ &= 1987 \times \left(\frac{1.54}{0.73} \right) \times \left[1 \pm \left(\frac{0.02}{1.54} + \frac{0.04}{0.73} \right) \right] \\ &= 4191.576 \pm 284.141 \text{ Kcal/Kg} \end{aligned}$$

Converting the gross calorific value into SI units, the uncertainty in measurement of GCV of banana stem was found to be $17.526 \pm 1.188 \text{ MJ/Kg.}$

Table 5.8: Uncertainty of Measurement of Proximate Analysis of Different Components of
Studied Biomass Species

Samples	Proximate analysis (wt.%, dry basis)			
	Moisture content	Ash content	Volatile matter	Fixed carbon content
Banana				
Leaf	6±2.00	17±0.00	63±4.00	14±2.00
Stem	5±1.41	10±1.41	65±1.41	20±3.16
Coconut				
Leaf	6±1.41	16±1.41	67±4.00	11±4.00
Shell	9±1.41	9±2.41	73±3.16	9±2.00
Pith	8±1.41	11±2.00	64±2.00	17±3.16
Arecanut				
Leaf	8±2.00	16±1.41	66±4.00	10±3.16
Coir	9±1.41	9±3.16	64±1.41	18±1.41
Wheat				
Stalk	11±2.00	6±2.00	65±2.00	18±2.00
Palm				
Leaf	12±2.00	6±4.00	65±4.00	17±2.00
Shell	8±1.41	3±1.41	72±3.16	17±3.16
Rice				
Stalk	10±4.00	33±4.00	45±2.00	12±2.00
Husk	7±1.41	19±2.00	62±4.00	12±3.16

Table 5.9: Uncertainty of Measurement of Gross Calorific Value of Different Components of
Studied Biomass Species

Sl. No	Sample	Gross Calorific Value (MJ/kg)	Uncertainty of Measurement
1	Banana Leaf	17.406	± 1.218
2	Banana Stem	17.523	± 1.188
3	Coconut Leaf	19.763	± 0.483
4	Coconut Shell	18.898	± 0.627
5	Coconut Pith	17.124	± 0.705
6	Arecanut Leaf	17.879	± 0.976
7	Arecanut Coir	16.565	± 0.574
8	Wheat Stalk	16.605	± 0.594
9	Palm Leaf	17.752	± 1.328
10	Palm Shell	18.155	± 1.142
11	Rice Stalk	14.242	± 0.752
12	Rice Husk	16.872	± 0.662

Table 5.10: Uncertainty of Measurement of Bulk Density of the Selected Biomass Species

Sl. No	Sample	Bulk Density (kg/m^3)	Uncertainty of Measurement
1	Banana Leaf	175.925	± 5.378
2	Banana Stem	120.370	± 2.898
3	Coconut Leaf	296.290	± 2.340
4	Coconut Shell	164.814	± 4.372
5	Coconut Pith	173.611	± 4.786
6	Arecanut Leaf	248.015	± 0.790
7	Arecanut Coir	187.982	± 5.488
8	Wheat Stalk	174.359	± 0.340
9	Palm Leaf	223.784	± 5.602
10	Palm Shell	108.673	± 3.682
11	Rice Stalk	156.364	± 2.496
12	Rice Husk	336.257	± 3.130

Table 5.11: Uncertainty of measurement of proximate analysis and gross calorific value of Coal-Biomass (Rice husk) Mixed Briquette in Different Ratios

Ratio (coal : biomass)	Proximate analysis (wt.% dry basis)				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	5±4.00	38±2.00	22±4.00	35±2.00	17.292±0.466
90 : 10	6±2.00	30±2.00	27±4.00	37±4.00	17.624±0.682
85 : 15	4±1.41	28±4.00	32±2.00	36±1.41	17.016±0.672

Table 5.12: Uncertainty of measurement of proximate analysis and gross calorific value of Coal-Biomass (Palm leaf) Mixed Briquette in Different Ratios

Ratio (coal : biomass)	Proximate analysis (wt.% dry basis)				Gross calorific value (MJ/kg)
	Moisture	Ash	Volatile matter	Fixed carbon	
100 : 0	5±4.00	38±2.00	22±4.00	35±2.00	17.292±0.466
90 : 10	6±2.00	29±1.41	28±2.00	37±1.41	17.672±1.282
85 : 15	7±2.00	28±2.00	30±2.00	35±2.00	18.213±1.683

5.8 Regression Analysis

The regression analysis has been performed on the data experimentally determined by proximate analysis, ultimate analysis and gross calorific values in order to develop regression equations for gross calorific value (GCV) as the function of variables associated with proximate and ultimate analyses and the findings have been listed in Tables 5.13 and 5.14.

5.8.1 Regression analysis performed on proximate analysis data

As discussed earlier in Section 5.2.1, the volatile matter and fixed carbon contents hugely affect the calorific value. On the other hand, moisture and ash contents have insignificant effects. So, these two variables were dropped in subsequent stages while developing regression equations. First, the moisture content was dropped and the regression equation for calorific value involving rest of the three variables was developed as follows:

$$\text{GCV} = -3.114 + 0.124 \times \text{AC} + 0.288 \times \text{VM} + 0.03 \times \text{FC} \quad (5.2)$$

where, GCV= predicted gross calorific value in MJ/kg

AC = ash content in wt. %

VM = volatile matter content in wt. %,

FC = fixed carbon content in wt. %,

Similarly, the regression equation involving three variables after dropping ash content was obtained as shown below:

$$\text{GCV} = 9.256 - 0.124 \times \text{MC} + 0.164 \times \text{VM} - 0.094 \times \text{FC} \quad (5.3)$$

where, MC = the moisture content in wt. %

Then, both the moisture and ash contents were dropped and the corresponding equation involving fixed carbon and volatile matter was found to be

$$\text{GCV} = 7.902 + 0.171 \times \text{VM} - 0.101 \times \text{FC} \quad (5.4)$$

Out of these two contents taking one at a time, two more regression were developed as follows:

$$\text{GCV} = 6.619 + 0.168 \times \text{VM} \quad (5.5)$$

$$\text{GCV} = 18.614 - 0.083 \times \text{FC} \quad (5.6)$$

The statistical performance measures such as R-squared value (R^2), R value (R), standard error of estimate (S), average bias error (ABE) and average absolute error (AAE) for all the above regression relationships shown in Equations 5.2-5.6 have been computed and listed in Table 5.13.

Table 5.13: Developed Regression Equations for the Estimation of the Gross Calorific Values of Studied Biomass Samples from Proximate Analysis Data and Their Statistical Performance Measures

Eq. No.	Regression equation	R-squared value (R ²)	R value (R)	Standard error of estimate (S)	Average bias error (ABE) (in %)	Average absolute error (AAE) (in %)
5.2	$GCV = -3.114 + 0.124 \times AC + 0.288 \times VM + 0.03 \times FC$	0.834	0.913	0.651	0.086	2.15
5.3	$GCV = 9.256 - 0.124 \times MC + 0.164 \times VM - 0.094 \times FC$	0.833	0.912	0.651	0.085	2.15
5.4	$GCV = 7.902 + 0.171 \times VM - 0.101 \times FC$	0.799	0.894	0.674	0.106	2.522
5.5	$GCV = 6.619 + 0.168 \times VM$	0.725	0.852	0.748	0.140	2.454
5.6	$GCV = 18.614 - 0.083 \times FC$	0.051	0.224	1.392	0.579	5.272

Table 5.13 shows that R² values of the Equations 5.2-5.4 has been found to be higher than 0.8 which suggests the existence of a strong correlation between GCV and independent variables. All these three equations have low values of standard error of estimate S (i.e., 0.651-0.674) which indicates smaller deviation of data points from the regression line. The lower values AAE of these three equations suggest less error in predicting GCV and more close to the

measured value of GCV. Further, as all the ABE values are positive the predictions of GCV are over-estimated and the values are low i.e., within 0.106 for these three equations.

Equation 5.5 shows a moderate value of R^2 (i.e., 0.725) suggesting average correlation between volatile matter and GCV. The standard error of estimate of this equation was found to be 0.748 which indicates deviation of some data points from the regression line. Further, AAE for this equation was found to be 2.454, suggesting some error in predicted GCV and positive values of ABE suggests that GCV is over-estimated by a margin 0.140. On the other hand, Equation 5.6 has a very low value of R^2 (i.e., 0.051) suggesting a weak correlation of fixed carbon FC upon GCV. This equation have higher values of standard errors of estimate (i.e., 1.392), indicating more deviation of data points from the regression line. Further, high AAE indicates more error in GCV and high positive values of ABE suggests that GCV is over-estimated by a margin 0.579.

Therefore, with higher R^2 value, lower S value and lower percentage of errors in terms of ABE or AAE, Equations 5.2-5.4 can be considered for prediction of GCV. Out of all regression equations developed, Equation 5.2 have been found to be the best with the highest R^2 value (0.834), lowest S value (0.651), and low values of ABE (0.086) and AAE (2.15). Hence, this regression equation should be considered to predict GCV.

5.8.2 Regression analysis performed on ultimate analysis data

All the four variables associated with ultimate analysis have been considered for developing regression equations for gross calorific value (GCV). Initially, equation for GCV was developed considering all the four variables i.e., O, N, C and H and the corresponding regression equation developed was:

$$\text{GCV} = 9.412 + 0.286 \times \text{C} - 0.555 \times \text{H} - 0.006 \times \text{O} - 0.078 \times \text{N} \quad (5.7)$$

As discussed earlier in Section 5.2.2, the calorific value of a solid fuel is not significantly affected by oxygen and nitrogen contents, hence these variables were dropped one by one and then both in the subsequent stages. Regression equations considering one variable at a time i.e., C or H were also developed. All these regression equations established for GCV are as follows:

$$\text{GCV} = 9.412 + 0.316 \times \text{C} - 0.787 \times \text{H} - 0.01 \times \text{O} \quad (5.8)$$

$$\text{GCV} = 9.361 + 0.279 \times \text{C} - 0.527 \times \text{H} - 0.085 \times \text{N} \quad (5.9)$$

$$\text{GCV} = 9.322 + 0.307 \times \text{C} - 0.774 \times \text{H} \quad (5.10)$$

$$\text{GCV} = 8.543 + 0.229 \times \text{C} \quad (5.11)$$

$$\text{GCV} = 10.577 + 1.391 \times \text{H} \quad (5.12)$$

where, GCV = predicted gross calorific value in MJ/kg

C = carbon in wt. %

H = hydrogen wt. %

O = oxygen in wt. %

N = nitrogen wt. %.

The statistical performance measures such as, R-squared value (R^2), R value (R), standard error of estimate (S), average bias error (ABE) and average absolute error (AAE) for all the above regression relationships have been computed and tabulated in Table 5.14.

Table 5.14: Developed Regression Equations for the Estimation of the Gross Calorific Values of Studied Biomass Samples from Ultimate Analysis Data and Their Statistical Performance Measures

Eq. No.	Developed equation	R-squared value (R ²)	R value (R)	Standard error of estimate (S)	Average bias error (ABE) (in %)	Average absolute error (AAE) (in %)
5.7	$GCV = 9.412 + 0.286 \times C - 0.555 \times H - 0.006 \times O - 0.078 \times N$	0.907	0.952	0.666	0.061	1.796
5.8	$GCV = 9.412 + 0.316 \times C - 0.787 \times H - 0.01 \times O$	0.905	0.951	0.601	0.063	1.862
5.9	$GCV = 9.361 + 0.279 \times C - 0.527 \times H - 0.085 \times N$	0.907	0.952	0.596	0.061	1.804
5.10	$GCV = 9.322 + 0.307 \times C - 0.774 \times H$	0.905	0.951	0.550	0.061	1.886
5.11	$GCV = 8.543 + 0.229 \times C$	0.864	0.929	0.609	0.087	2.395
5.12	$GCV = 10.577 + 1.391 \times H$	0.456	0.675	1.219	0.391	5.441

From Table 5.14 it can be observed that, R^2 values of the Equations 5.7-5.10 have been found to be higher than 0.9 which suggests the existence of a strong correlation of the independent variables upon GCV. All these four equations have low values of standard error of estimate S (i.e., 0.550-0.666) which indicates smaller deviation of data points from the regression line. The lower values of AAE of these four equations suggest less error in predicting GCV and more close to the measured value of GCV. Further as all the ABE values are positive, the predictions of GCV are over-estimated and the values are low i.e., within 0.063 for all these four equations.

In case of Equation 5.12, R^2 value has been found to be 0.456 suggesting a weak correlation between H and GCV, when H was considered as single independent variable. The high values standard errors of estimate (i.e., 1.219) of this equation indicate more deviation of data points from the regression line. Further, higher values of AAE indicate more error in GCV and positive values of ABE suggests that the predicted GCV is over-estimated by a margin of 0.391.

Therefore, with higher R^2 value, lower S value and lower percentage of errors in terms of ABE or AAE, Equations 5.7-5.10 can be considered for prediction of GCV. Out of all regression equations developed, Equation 5.7 has been found out to be the best with the highest R^2 value (0.907), lower S value (0.666), and lower values of ABE (0.061) and AAE (1.796). Hence, this regression equation should be considered to predict GCV.

5.9 An Approach for Decentralized Power Generation and Energy Plantation Structure

A cluster of 10-12 villages consisting of nearly 2000 families was considered to assess the electricity requirement and one power plant can be designed accordingly. Approximately 2 kWh/day is the electricity requirement per family for domestic purposes [64]. Considering an additional 11000 kWh/day (approx.) of energy for irrigational purposes and small-scale

industries around the villages, a power plant should be designed which can generate 15 MWh (i.e., $2 \times 2000 + 11000$) of electricity per day which is same as 5475 MWh/year (i.e., 15×365).

5.9.1 Land requirement for biomass

The rates of production of different components of selected agricultural biomass species viz., banana, coconut, arecanut, palm, wheat and rice in tonnes per hectare (i.e., t/ha) on dry basis were obtained from field studies and are shown in Tables 5.15-5.20. The gross calorific values in MJ/kg of these components shown in Table 5.3 were converted into MJ/t and are listed in these tables. The energy content (i.e., in MJ/ha) of different residual components of selected agricultural species as listed in these tables, was found out by multiplying the gross calorific value (i.e., in MJ/t) with the amount of residues produced per hectare (i.e., in t/ha).

Table 5.15: Total Energy Contents and Power Generation Structure for Banana

Component	Gross Calorific value (MJ/t, dry basis)	Biomass production (t/ha, dry basis)	Energy content (MJ/ha)
Leaf	17.406×10^3	0.91	15.839×10^3
Stem	17.523×10^3	0.09	1.577×10^3

Table 5.16: Total Energy Contents and Power Generation Structure from Coconut Biomass

Species

Component	Gross Calorific value (MJ/t, dry basis)	Biomass production (t/ha, dry basis)*	Energy content (MJ/ha)
Shell	18.898×10^3	5.00	94.490×10^3
Pith	17.124×10^3	2.50	42.810×10^3
Leaf	19.763×10^3	1.34	26.482×10^3

Table 5.17: Total Energy Contents and Power Generation Structure from Arecanut Biomass

Species

Component	Gross Calorific value (MJ/t, dry basis)	Biomass production (t/ha, dry basis)	Energy content (MJ/ha)
Leaf	17.879×10^3	0.55	9.784×10^3
Coir	16.565×10^3	2.36	39.093×10^3

Table 5.18: Total Energy Contents and Power Generation Structure from Rice Biomass Species

Component	Gross Calorific value (MJ/t, dry basis)	Biomass production (t/ha, dry basis)*[65]	Energy content (MJ/ha)
Husk	16.872×10^3	3.5	59.052×10^3
Stalk	14.242×10^3	1.1	15.866×10^3

Table 5.19: Total Energy Contents and Power Generation Structure from Wheat Biomass Species

Component	Gross Calorific value (MJ/t, dry basis)	Biomass production (t/ha, dry basis)	Energy content (MJ/ha)
Stalk	16.605×10^3	1.7	28.228×10^3

Table 5.20: Total Energy Contents and Power Generation Structure from Palm Biomass Species

Component	Gross Calorific value (MJ/t, dry basis)	Biomass production (t/ha, dry basis)*	Energy content (MJ/ha)
Leaf	17.752×10^3	1.84	32.663×10^3
Shell	18.155×10^3	4.01	72.802×10^3

Calculation for Land Requirement for Energy Plantation

The thermal efficiency of biomass fuelled heat engine and the overall efficiency of the power plant have been considered as 27 % and 85 % respectively. Using the values of energy contents shown in Tables 5.15-5.20, calculations have been done to find out land required in hectares for energy plantation in order to have continuous generation of electricity at the rate of 5475 MWh/year. A sample calculation for coconut plant has been shown in next paragraph.

Sample calculation for land requirement for coconut plant

Adding the energy contents of all the waste components obtained from coconut plant, the total energy available per hectare of land is obtained as $(94.490 + 42.810 + 26.482) \times 10^3 \text{ MJ/ha} = 163.78 \times 10^3 \text{ MJ/ha}$.

Energy output from coconut biomass from one hectare of land considering 27 % thermal efficiency = $163.78 \times 10^3 \times 0.27 = 44221.14 \text{ MJ} = 44221.14 \times 0.0002777778 = 12.28365 \text{ MWh}$.

Power generation considering 85 % overall efficiency = $12.28365 \times 0.85 = 10.441103 \text{ MWh/ha}$.

Therefore, land required to supply electricity from coconut biomass species for the whole year =

$$\frac{5475}{10.441103} = 524.37 \text{ hectares} \equiv 524 \text{ hectares.}$$

The above procedure was followed to calculate land required for energy plantation for the rest of the selected agricultural biomass species and the results have been outlined in Table 5.21.

Table 5.21: Land Required for Energy Plantation of Different Agricultural Biomass Species for generating 15 MWh per day

Sl. No.	Biomass Species	Land Required (ha)
1.	Banana	4931
2.	Coconut	524
3.	Arecanut	1757
4.	Palm	814
5.	Wheat	3043
6.	Rice	1146

5.9.2 Fuel Requirement for co-firing with biomass

Power generation structure for briquettes of coal made by mixing with rice husk and also with palm leaf in different ratios was developed. Referring Tables 5.5-5.6, the gross calorific values in MJ/kg of the briquettes were converted to MJ/t and shown in Tables 5.22 and 5.23 for both the biomass species.

Table 5.22: Energy Content from Coal-Rice Husk Blends

Sl. No.	Proportions of components (wt.%)		Energy content (MJ/t)
	Coal	Rice Husk	
1.	100	0	17292
2.	90	10	17624
3.	85	15	17016

Table 5.23: Energy Content from Coal-Palm Leaf Blends

Sl. No.	Proportions of components (wt.%)		Energy content (MJ/t)
	Coal	Palm Leaf	
1.	100	0	17292
2.	90	10	17672
3.	85	15	18213

Considering the thermal efficiency of biomass fuelled heat engine and the overall efficiency of the power plant to be 27 % and 85 % respectively, calculations have been done to determine the amount of fuels required to maintain electricity requirements (i.e., 5475 MWh/year) and the

results have been outlined in Tables 5.24-5.25. The sample calculation of fuel requirement for coal-rice husk mixed briquette has been shown below for various ratios.

a) Amount of fuel required when proportion of coal-rice husk is 100:0 (i.e., 100 % coal)

Referring Table 5.22, energy content of briquette made of 100% coal = 17292 MJ/t

Total work output from 1 tonne of coal at 27 % of thermal efficiency of biomass fuelled heat engine = $17292 \times 0.27 = 4668.84$ MJ/t.

Total electricity generated considering 85 % overall efficiency of a thermal power plant = $4668.84 \times 0.85 = 3968.51$ MJ/t = $3968.51 \times 0.000277777778$ MWh/t = 1.102 MWh/t

Thus, the amount of coal required to supply electricity of 5475 MWh for the whole year =

$$\frac{5475 \text{ MWh/year}}{1.102 \text{ MWh/t}} = 4968.24 \text{ t/year} \equiv 4968 \text{ t/year.}$$

b) Amount of fuel required when proportion of coal-rice husk is 90:10 (i.e., 90 % coal and 10 % rice husk)

Referring Table 5.22, energy content of briquette made of 90 % coal and 10 % rice husk = 17624 MJ/t

Total work output from 1 tonne of coal-rice husk briquette at 27 % of thermal efficiency of biomass fuelled heat engine = $17624 \times 0.27 = 4758.48$ MJ/t.

Total electricity generated considering 85 % overall efficiency of a thermal power plant = $4758.48 \times 0.85 = 4044.71$ MJ/t = $4044.71 \times 0.000277777778$ MWh/t = 1.124 MWh/t.

Thus, the amount of coal and rice husk required to supply electricity of 5475 MWh for the whole year = $\frac{5475 \text{ MWh/year}}{1.124 \text{ MWh/t}} = 4870.99 \text{ t/year} \equiv 4871 \text{ t/year}$.

The corresponding amounts of coal required = $4871 \times 0.90 \text{ t/year} = 4383.9 \text{ t/year}$.

Similarly, the amount of rice husk required = $4871 \times 0.10 \text{ t/year} = 487.1 \text{ t/year}$.

c) Amount of fuel required when proportion of coal-rice husk is 85:15 (i.e., 85 % coal and 15 % rice husk)

Referring Table 5.22, energy content of briquette made of 85 % coal and 15 % rice husk = 17016 MJ/t

Total work output from 1 tonne of coal-rice husk briquette at 27 % of thermal efficiency of biomass fuelled heat engine = $17016 \times 0.27 = 4594.32 \text{ MJ/t}$.

Total electricity generated considering 85 % overall efficiency of a thermal power plant = $4594.32 \times 0.85 = 3905.17 \text{ MJ/t} = 3905.17 \times 0.000277777778 \text{ MWh/t} = 1.085 \text{ MWh/t}$.

Thus, the amount of coal and rice husk required to supply electricity of 5475 MWh for the whole year = $\frac{5475 \text{ MWh/year}}{1.085 \text{ MWh/t}} = 5046.08 \text{ t/year} \equiv 5046 \text{ t/year}$.

The corresponding amounts of coal required = $5046 \times 0.85 \text{ t/year} = 4289.1 \text{ t/year}$.

Similarly, the amount of rice husk required = $5046 \times 0.15 \text{ t/year} = 756.9 \text{ t/year}$.

The amounts of different fuel required annually have been found out and listed in Table 5.24.

Tables 5.24: Fuel Required for Coal-Rice Husk Briquettes

Sl. No.	Proportions of Components (wt. %)		Fuel Required (t/year)		
	Coal	Rice husk	Coal	Rice husk	Total
1.	100	0	4968.0	0	4968
2.	90	10	4383.9	487.1	4871
3.	85	15	4289.1	756.9	5046

Similarly following the above procedure, the amount of fuel required for coal-palm leaf briquettes was calculated and listed in Table 5.25.

Tables 5.25: Fuel Required for Coal-Palm Leaf Briquettes

Sl. No.	Proportions of Components (wt. %)		Fuel Required (t/year)		
	Coal	Palm leaf	Coal	Palm leaf	Total
1.	100	0	4968.0	0	4968
2.	90	10	4375.8	486.2	4862
3.	85	15	4008.6	707.4	4716

Tables 5.24-5.25 show the requirement of coal and biomass in tonnes per year for making briquettes of coal-rice husk and coal-palm leaf respectively with biomass ratio varying from 0 to 15 % so as to maintain a continuous generation of electricity at the rate of 5475 MWh/year.

Chapter 6

CONCLUSIONS

- *Conclusions*
- *Scope for Future Work*

6. CONCLUSIONS

6.1 Conclusions

Based on the experimental results carried out in this work, the following conclusions can be summarized.

- a) The ash content of rice stalk i.e., 33 wt.% has been found to be the highest among all the studied samples. This is a matter of concern, as the high values of ash content affects the efficiency of the boiler, and causes clinkering and slagging problems.
- b) The coconut shell has been found to have the highest volatile matter (i.e., 73 wt.%) among the agricultural wastes studied. A high value of volatile matter contributes towards high value of its gross calorific value.
- c) Banana stem has been reported to have the highest fixed carbon content i.e., 20 wt% among the studied biomass samples which suggests that it will generate higher amount of heat inside the boiler.
- d) The leaves and shells of coconut have been found to have calorific values (i.e., above 18 MJ/kg) as well as their corresponding carbon (i.e., above 43 wt.%) and hydrogen (i.e., above 4.5 wt.%) contents in the higher range among all the studied samples. Hence, they can also have significant contribution towards power generation.
- e) Initial deformation temperatures (IDTs) of all the studied samples are found to be in the range 938-1137 °C which is considerably above the safe boiler temperature i.e. around 800 °C. This indicates that all the studied samples can be safely used as solid fuels for

combustion in boilers without any possibility of clinker formation and other ash related problems up to a temperature of around 900 °C.

- f) The mixed briquette of coal-palm leaf in the ratio 85:15 showed the highest calorific value among the selected samples which suggests that a portion of fossil fuel can be replaced effectively by biomass without affecting the design parameters of the boiler.
- g) Regression equations developed were found to be with error within acceptable limits. Recommended regression equations are $GCV = -3.114 + 0.124 \times AC + 0.288 \times VM + 0.03 \times FC$ (on the basis of proximate analysis) and $GCV = 9.412 + 0.286 \times C - 0.555 \times H - 0.006 \times O - 0.078 \times N$ (on the basis of ultimate analysis).
- h) Approximately 4931, 524, 1757, 814, 3043 and 1146 hectares of land area are required for harvesting banana, coconut, arecanut, palm, wheat and rice biomass species in order to have uninterrupted generation of electricity at the rate of 15 MWh per day. Coconut is found to be the prime candidate with the lowest amount of land requirement (i.e., 524 hectares) for energy plantation and its exploitation as a fuel in power generation.
- i) On the basis of the energy value and land requirement results obtained in the present study, coconut biomass appears to be the best candidate for exploitation in power generation.

6.2 Scope for Future Work

Exploring and exploiting different biomass species for power generation has immense scope and it can be crucial for energy generation in future. The following suggestions may be considered to strive forward research work in future.

- a) Similar kind of study should be extended for the other agricultural wastes.

- b) Studies can be made for improving the efficiencies of existing biomass fuelled power plants.
- c) In addition to the above, attention of scientists and technocrats needs to be directed towards improving the yields of biomass per hectare of land.

REFERENCES

References

- [1] Raghuvarshi S. P., Chandra A. and Raghav A. K. Carbon dioxide emissions from coal based power generation in India, *Energy Conversion and Management*, 47 (2006): pp. 427-441
- [2] Ministry of new and renewable energy. Grid interactive and off-grid renewable power, New Delhi: Government of India, <http://mnre.gov.in/file-manager/annual-report/2010-2011/EN/Chapter%205/chapter%205.htm> (2011)
- [3] Ministry of Agriculture. Annual Report 2014, <http://agricoop.nic.in/Annualreport2013-14/artp13-14ENG.pdf> (2014)
- [4] Ministry of Statistics and Programme Implementation. Energy Statistics 2014, http://mospi.nic.in/mospi_new/upload/Energy_stats_2014.pdf (2014)
- [5] Kumar M. and Patel S. K. Energy values and estimation of power generation potentials of some non-woody biomass species, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 30 (2008): pp. 765-773
- [6] Kumar M., Patel S. K. and Mishra S. Studies on characteristics of some shrubaceous non-woody biomass species and their electricity generation potentials, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 32 (2010): pp. 786-795
- [7] International Energy Agency, Key World Energy Statistics, <http://www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf> (2013)
- [8] Renewable energy policy network for the 21st century, Global Status Report 2012, www.map.ren21.net/GSR/GSR2012_low.pdf (2012)
- [9] Renewable energy policy network for the 21st century, Global Status Report 2013, http://www.ren21.net/portals/0/documents/resources/gsr/2013/gsr2013_lowres.pdf (2013)

- [10] Renewable energy policy network for the 21st century, Global Status Report 2014, www.ren21.net/portals/0/.../2014/gsr2014_full%20report_low%20res.pdf (2014)
- [11] India's energy scenario in 2013 - challenges and prospects, Hydrocarbon Asia, (2013): pp. 6-10, <http://www.hcasia.safan.com/mag/hcajanmar13/r06.pdf>
- [12] EPA Combined Heat and Power Partnership, http://www.epa.gov/chp/documents/biomass_chp_catalog_part5.pdf (2002)
- [13] Federal Technology Alert, A new technology demonstration publication, <http://www.nrel.gov/docs/fy04osti/33811.pdf> (2004)
- [14] Kurchania A. K. Biomass Energy, Chapter 2, http://www.springer.com/cda/content/document/cda_downloaddocument/9783642284175-c2.pdf (2014)
- [15] Kishore V. V. N. and Mande S. Development benefits of clean energy in India: Biomass gasification prospects in India, The William and Flora Hewlett Foundation. New Delhi: The Energy and Resources Institute (2007)
- [16] Das B. K. and Hoque S. M. N. Assessment of the potential of biomass gasification for electricity generation in Bangladesh, Journal of Renewable Energy, <http://dx.doi.org/10.1155/2014/429518> (2014)
- [17] Wyman C. E. Ethanol from lignocellulosic biomass: technology, economics, and opportunities, Bioresource Technology, 50 (1994): pp. 3-15
- [18] Biomass Co-firing, IEA-ETSAP and IRENA Technology Brief E21, <http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E21%20Biomass%20Co-firing.pdf> (2013)

- [19] Ministry of Statistics and Programme Implementation. Energy Statistics 2014. http://mospi.nic.in/mospi_new/upload/Energy_stats_2014.pdf (2014)
- [20] Rastogi C. Changing geo-politics of oil and the impact on India, *Procedia-Social and Behavioral Sciences*, 133 (2014): pp. 93-105
- [21] Parikh J. and Parikh K. India's energy needs and low carbon options, *Energy*, 36 (2011): pp. 3650-3658
- [22] Bhattacharya S. and Jana C. Renewable energy in India: historical developments and prospects, *Energy*, 34 (2009): pp. 981-991
- [23] Blenkinsopp T., Coles S. and Kirwan K. Renewable energy for rural communities in Maharashtra, India, *Energy Policy*, 60 (2013): pp. 192-199
- [24] Pillai I. R. and Banerjee R. Renewable energy in India: status and potential, *Energy*, 34 (2009): pp. 970-980
- [25] Gera R., Rai H., Parvej Y. and Soni H. Renewable energy scenario in India: opportunities and challenges, *Indian Journal of Electrical and Biomedical Engineering*, 1 (2013): pp. 10-16
- [26] Werther J., Saenger M., Hartge E. U., Ogada T. and Siagi Z. Combustion of agricultural residues, *Progress in Energy and Combustion Science*, 26 (2000): pp. 1-27
- [27] Cherubini F. and Ulgiati S. Crop residues as raw materials for biorefinery systems – A LCA case study, *Applied Energy*, 87 (2010): pp. 47-57
- [28] Chauhan S. Biomass resources assessment for power generation: a case study from Haryana state, India, *Biomass and Bioenergy*, 34 (2010): pp. 1300-1308
- [29] Chauhan S. District wise agriculture biomass resource assessment for power generation: a case study from an Indian state, Punjab, *Biomass and Bioenergy*, 37 (2012): pp. 205-212

- [30] Williams A., Jones J. M., Ma L. and Pourkashanian M. Pollutants from the combustion of solid biomass fuels, *Progress in Energy and Combustion Science*, 38 (2012): pp. 113-137
- [31] Cardozo E., Erlich C., Alejo L. and Fransson T. H. Combustion of agricultural residues: an experimental study for small-scale applications, *Fuel*, 115 (2014): pp. 778-787
- [32] Mukunda H., Dasappa S., Paul P., Rajan N. and Shrinivasa U. Gasifiers and combustors for biomass–technology and field studies, *Energy for Sustainable Development*, 1 (1994): pp. 27-38
- [33] Küçük M. M. and Demirbaş A. Biomass conversion processes, *Energy Conversion and Management*, 38 (1997): pp. 151-165
- [34] Chum H. L. and Overend R. P. Biomass and renewable fuels, *Fuel Processing Technology*, 71 (2001): pp. 187-195
- [35] Wander P. R., Altafini C. R. and Barreto R. M. Assessment of a small sawdust gasification unit, *Biomass and Bioenergy*, 27 (2004): pp. 467-476
- [36] Dixit C. S. B., Paul P. J. and Mukunda H. S. Part I: Experimental studies on a pulverised fuel stove, *Biomass and Bioenergy*, 30 (2006): pp. 673-683
- [37] Demirbas A. Progress and recent trends in biofuels, *Progress in Energy and Combustion Science*, 33 (2007): pp. 1-18
- [38] Nussbaumer T. Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction, *Energy and Fuels*, 17 (2003): pp. 1510-1521
- [39] Fang X. and Jia L. Experimental study on ash fusion characteristics of biomass, *Bioresource Technology*, 104 (2012): pp. 769-774
- [40] Vamvuka D. and Kakaras E. Ash properties and environmental impact of various biomass and coal fuels and their blends, *Fuel Processing Technology*, 92 (2011): pp. 570-581

- [41] Niu Y., Tan H., Wang X., Liu Z., Liu H., Liu Y. and Xu T. Study on fusion characteristics of biomass ash, *Bioresource Technology*, 101 (2010): pp. 9373-9381
- [42] Xiao R., Chen X., Wang F. and Yu G. The physicochemical properties of different biomass ashes at different ashing temperature, *Renewable Energy*, 36 (2011): pp. 244-249
- [43] Hoffmann B. S., Szklo A. and Schaeffer R. An evaluation of the techno-economic potential of co-firing coal with woody biomass in thermal power plants in the south of Brazil, *Biomass and Bioenergy*, 45 (2012): pp. 295-302
- [44] Tillman D. A. Biomass cofiring: the technology, the experience, the combustion consequences, *Biomass and Bioenergy*, 19 (2000): pp. 365-384
- [45] Parikh J., Channiwala S. and Ghosal G. A correlation for calculating elemental composition from proximate analysis of biomass materials, *Fuel*, 86 (2007): pp. 1710-1719
- [46] Majumder A., Jain R., Banerjee P. and Barnwal J. Development of a new proximate analysis based correlation to predict calorific value of coal, *Fuel*, 87 (2008): pp. 3077-3081
- [47] Erol M., Haykiri-Acma H. and Küçükbayrak S. Calorific value estimation of biomass from their proximate analyses data, *Renewable Energy*, 35 (2010): pp. 170-173
- [48] Yin C. Y. Prediction of higher heating values of biomass from proximate and ultimate analyses, *Fuel*, 90 (2011): pp. 1128-1132
- [49] Nhuchhen D. R. and Abdul Salam P. Estimation of higher heating value of biomass from proximate analysis: a new approach, *Fuel*, 99 (2012): pp. 55-63
- [50] Kumar M., Patel S. K. and Hamid P. F. Characteristics of some forestry non-woody biomass species and estimation of their power generation potentials, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 33 (2011): pp. 1616-1624

- [51] Bureau of Indian Standards, IS: 1350 Part I - Methods of Tests for Coal and Coke. New Delhi, (1984): pp. 3-28.
- [52] Quaak P., Knoef H. and Stassen H. Energy from biomass, World Bank Technical Paper (1999)
- [53] Agrawal B. and Jain S. A textbook of metallurgical analysis, 3rd Edition. New Delhi: Khanna Publishers (1980)
- [54] Kumar M., Patel S. K. and Hamid P. Characteristics of some forestry non-woody biomass species and estimation of their power generation potentials, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 33 (2011): pp. 1616-1624
- [55] German Standard DIN: 51730. Testing of Solid Fuels—Determination of Fusibility of Fuel Ash Berlin, Germany: German Institute for Standardization (1984)
- [56] Parikh J., Channiwala S. and Ghosal G. A correlation for calculating HHV from proximate analysis of solid fuels, Fuel, 84 (2005): pp. 487-494
- [57] García R., Pizarro C., Lavín A. G. and Bueno J. L. Spanish biofuels heating value estimation. Part II: Proximate analysis data, Fuel, 117 (2014): pp. 1139-1147
- [58] García R., Pizarro C., Lavín A. G. and Bueno J. L. Spanish biofuels heating value estimation. Part I: Ultimate analysis data, Fuel, 117 (2014): pp. 1130-1138
- [59] Johnson R. A., Probability and statistics for engineers. New Delhi, Prentice Hall of India, (1995)
- [60] Levin R. I. and Rubin D. S. Statistics for management. New Delhi, Pearson Education, (1998)
- [61] Spiegel M. R. Theory and problems of statistics. Singapore, McGraw-Hill, (1992)

- [62] Ahmaruzzaman M. Proximate analyses and predicting HHV of chars obtained from cocracking of petroleum vacuum residue with coal, plastics and biomass, *Bioresource Technology*, 99 (2008): pp. 5043-5050
- [63] Dodd V. A. and Grace P. M. Agricultural engineering, Power, processing and systems: Proceedings of the Eleventh International Congress on Agricultural Engineering, Dublin, CRC Press, 4 (1989)
- [64] Kumar M. and Gupta R. Power generation from biomass, *Encology*, 6 (1991): pp. 9-14
- [65] Patel S. K. and Kumar M. Electrical power generation potential of paddy waste, Proceedings of International Conference on Renewable Energy Generation and Applications, UAE University, (2010): pp. 117.1-117.3

BIO DATA

Name: Satyabrata Tripathy

Email: Satyabrata.tripathy86@gmail.com

Mobile: 08596806058

Personal Details

Father's name: Hare Krushna Tripathy

Mother's name: Annapurna Tripathy

Gender: Male

Date of birth: 29th November 1986

Nationality: Indian

Permanent Address

Satyabrata Tripathy

Qr. No. – A/10

Sector - 7

Rourkela – 769003

Odisha

Education

- Currently pursuing Master in Technology (By Research) in Dept. of Mechanical Engineering, National Institute of Technology, Rourkela. Thesis submitted, awaiting review.
- Completed Bachelor in Technology in Dept. of Mechanical Engineering from Institute of Technical Education and Research, Siksha 'O' Anusandhan University in 2011

International Conference

- Tripathy S, Patel S. K. and Kumar M., Characterisation of the Properties of Different Agricultural Based Biomass and Estimation of their Power Generation Potentials, Proceedings of International Conference on Emerging Trends in Engineering and Technology (2013): pp. 171-176

Paper Communicated

- Tripathy S., Patel S. K. and Kumar M. Experimental Investigation on the Properties of Agricultural Residues and Estimation of Their Power Generation Potentials, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. Taylor & Francis Group, United Kingdom.
- Tripathy S., Patel S. K. and Kumar M. Prediction of Higher Heating Value of Biomass from Proximate and Ultimate Analyses: An Analytic Approach, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. Taylor & Francis Group, United Kingdom.